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LANDSAT-5 ORBIT ADJUST MANEUVER REPORT

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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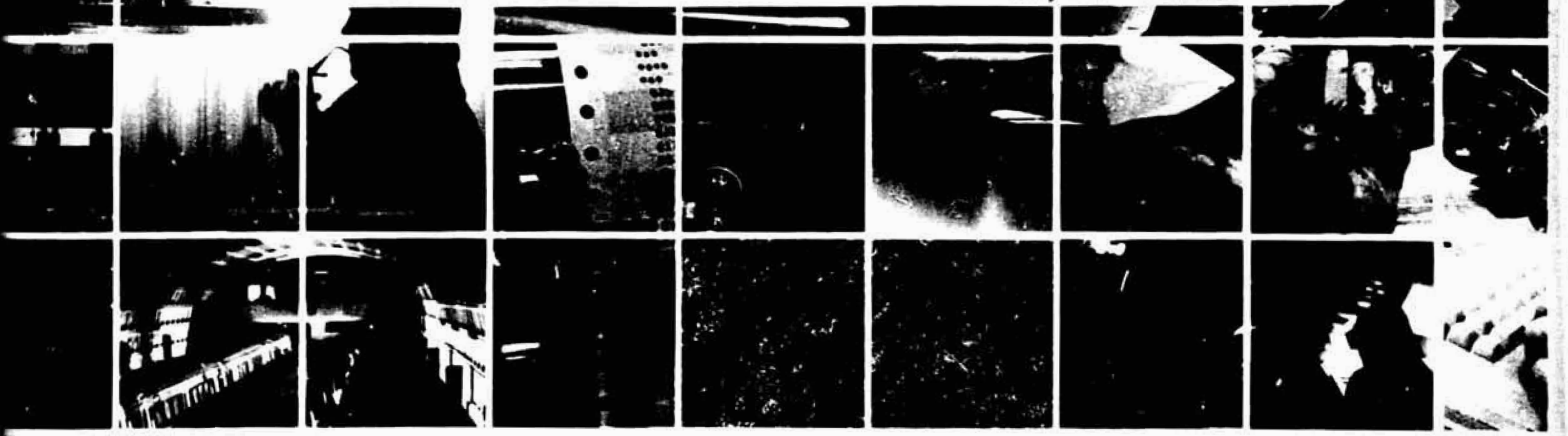

CSC
COMPUTER SCIENCES CORPORATION

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Prepared for

GODDARD SPACE FLIGHT CENTER

By

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Under

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ABSTRACT

The Landsat-5 spacecraft was successfully launched from the Western Test Range by a Delta 3920 launch vehicle on March 1, 1984. This document describes the orbit adjust maneuvers performed to raise the spacecraft to mission altitude, synchronize it with the required groundtrack, and properly phase the spacecraft with Landsat-4 to provide an 8-day full Earth coverage cycle. It also describes maneuver planning and evaluation procedures, data and analysis results for all maneuvers performed to date, the frozen orbit concept, and the phasing requirement between Landsat-4 and Landsat-5.

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SECTION 1 - INTRODUCTION

The Landsat-5 spacecraft was successfully launched from the Western Test Range by a Delta 3920 launch vehicle on March 1, 1984. The launch was very near nominal and resulted in an orbit that was approximately 12 kilometers below the final mission altitude. The orbit was targeted low intentionally to ensure that no orbit lowering maneuvers would be required (this would necessitate a 180-degree yaw of the spacecraft, which is undesirable). A series of eight orbit raising maneuvers was performed between March 7 and April 4, 1984, to raise the semimajor axis the remaining 12 kilometers. The maneuvers were performed at the proper times so that both phasing with the World Reference System (WRS) groundtrack grid and an 8-day coverage cycle between Landsat-4 and Landsat-5 were achieved. The series of maneuvers also achieved a frozen orbit. Periodic orbit maintenance maneuvers have kept the groundtrack within the required bounds.

This document follows the format of the Landsat-4 Orbit Adjust Maneuver Report (Reference 1) prepared by R. J. McIntosh. Section 2 defines the Landsat-5 orbit requirements, discusses computer software and operational procedures used for maneuver planning and evaluation, and briefly describes the frozen orbit concept. Also discussed is the phasing requirement between Landsat-4 and Landsat-5 needed to achieve the 8-day coverage cycle. Section 3 describes the postlaunch injection error removal maneuver sequence and discusses orbit maintenance maneuvers. The appendix contains data and analysis results covering all maneuvers performed to date. It is intended that update pages will be published for insertion into the appendix as future maneuvers are performed.

SECTION 2 - MANEUVER PLANNING AND EVALUATION

This section defines the Landsat-5 mission orbit and groundtrack and discusses computer software and procedures used for premaneuver planning and postmaneuver evaluation. In addition, brief descriptions of the frozen orbit concept and the phasing requirement between Landsat-4 and Landsat-5 are given.

2.1 LANDSAT-5 MISSION ORBIT REQUIREMENTS

The nature of the Landsat-5 mission requires that the spacecraft orbit have the proper altitude and inclination to maintain a Sun-synchronous node rate (mean local time at any descending node crossing is constant) and a 16-day groundtrack repeat cycle. The number of orbits in the groundtrack repeat cycle is 233; that is, after 233 orbits, the spacecraft must cross over the same longitude point on the Earth's Equator. The nominal mean semimajor axis required for this repeat cycle is approximately 7077.8 kilometers. The WRS groundtrack grid defines a series of descending node crossings equally spaced around the Earth's Equator, approximately 172 kilometers apart, with the base longitude defined as 295.4 degrees east longitude. An orbital inclination of approximately 98.2 degrees maintains the required Sun-synchronous nodal regression rate and mean local time of the descending node (between 9:30 and 10:00 a.m.). The orbit requirements are defined in Reference 2.

2.2 FROZEN ORBIT CONCEPT

Low-altitude circular orbits are subject to strong perturbations from the oblate Earth's gravitational potential. The magnitude of the effects of these perturbations depends on the initial values of certain orbital parameters, namely, semimajor axis, eccentricity, inclination, and argument of perigee. By targeting toward the proper values of these orbital parameters, the effects of certain perturbations can be minimized. This is the case of the frozen orbit, in which the line of apsides (the line joining apogee and perigee) is stopped or frozen. For a near-circular orbit, the changes in the average argument of perigee ($\bar{\omega}$) and the average eccentricity ($\bar{e}$) become zero when $\bar{\omega}$ equals 90 degrees and $\bar{e}$ approaches some determinable small value. This value of $\bar{e}$ (the frozen eccentricity) is a function of the averaged semimajor axis ($\bar{a}$) and inclination ($\bar{i}$). The frozen eccentricity for the Landsat-5 orbit is approximately 0.0012. For initial values of $\bar{\omega}$ near 90 degrees and initial values of $\bar{e}$ near the frozen eccentricity, the averaged argument of perigee and eccentricity oscillate within a small range about the frozen condition. Figure 2-1 shows the evolution of $\bar{e}$ and $\bar{\omega}$ with time for a near-frozen Landsat-5 orbit.

The evolution of a near-frozen orbit can be described in an eccentricity vector space, where the motion of the eccentricity and argument of perigee about the frozen point is circular. An example of a satellite with $\bar{e}$ and $\bar{\omega}$ near the frozen values is illustrated in Figure 2-2, using the eccentricity vector space representation ($\bar{e} \cos \bar{\omega}$ and $e \sin \bar{\omega}$). Any set of initial conditions, such as point A in Figure 2-2, results in the cyclic evolution of the $\bar{e} \cos \bar{\omega}$ and $\bar{e} \sin \bar{\omega}$ parameters. The frozen orbit concept is developed in Reference 3.

The main advantage of the frozen orbit is a minimum variation in altitude above any given latitude due to a near-constant perigee location. A near-constant altitude above a given latitude will minimize the necessary geometric corrections to the Landsat-5 images. The frozen orbit is a derived requirement for Landsat-5. The eccentricity will

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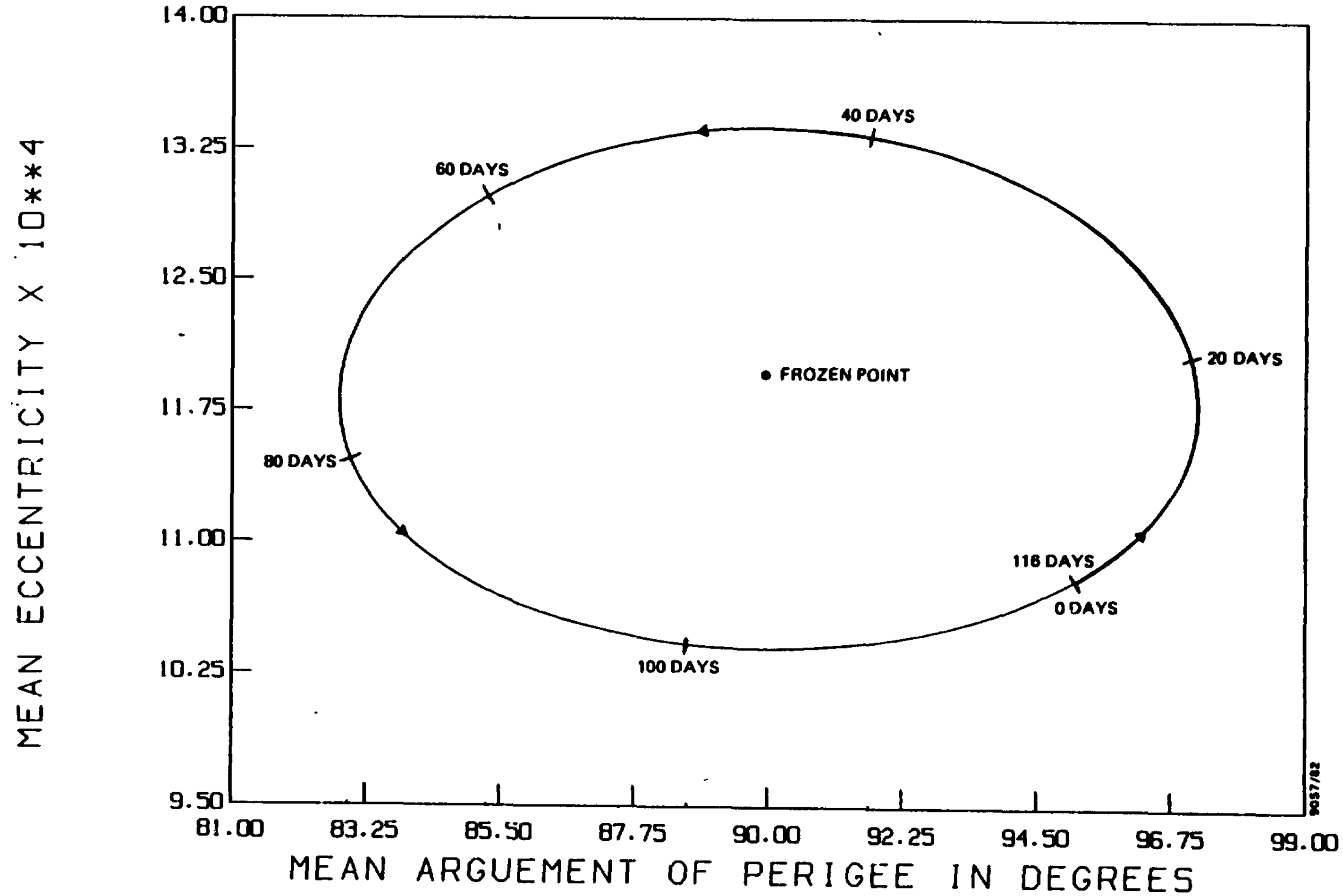

Figure 2-1. Evolution of $\bar{e}$ and $\bar{\omega}$ for a Near-Frozen Landsat-5 Orbit

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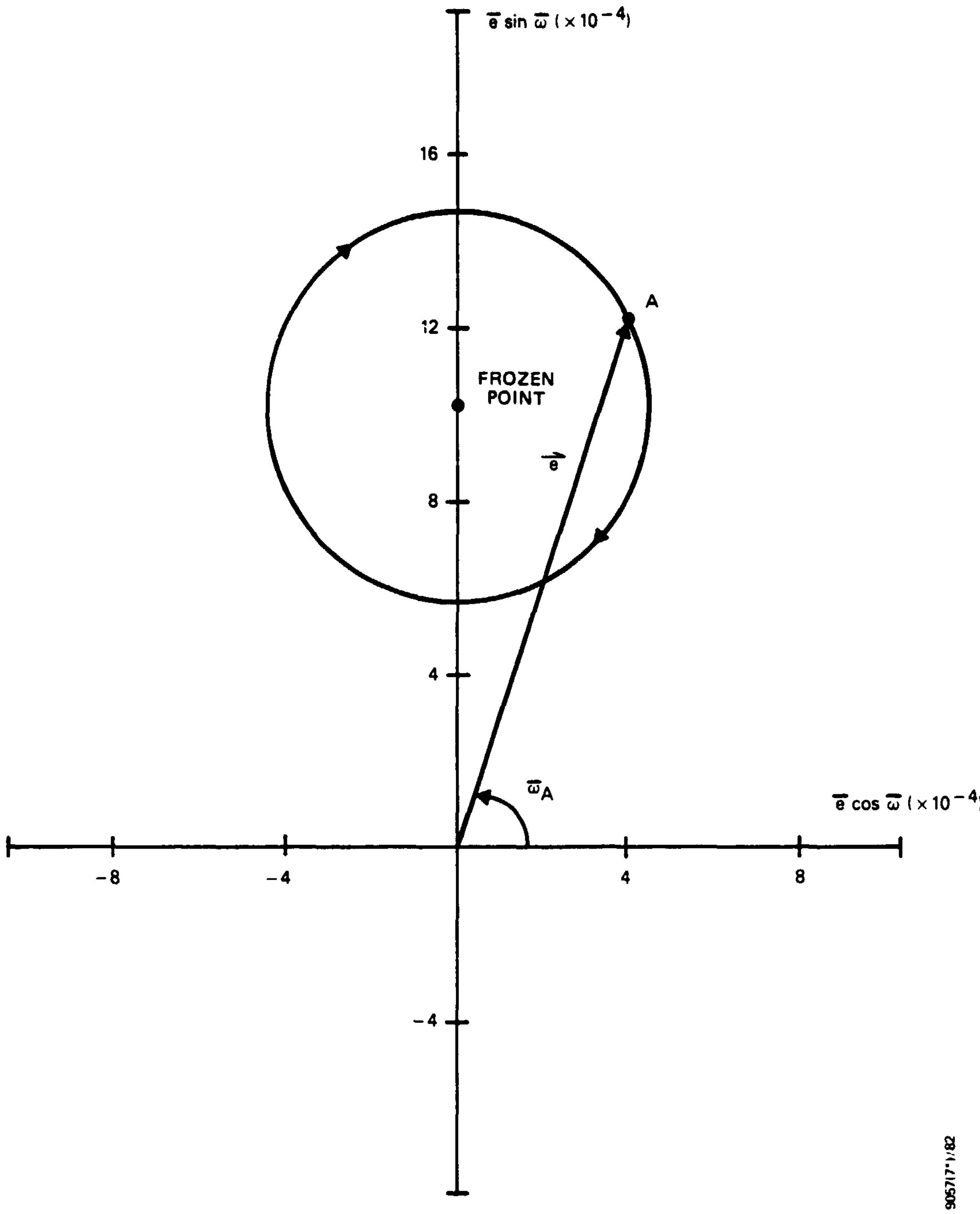

Figure 2-2. Oscillation of $\bar{e}$ and $\bar{\omega}$ About Frozen Point for a Typical Near-Frozen Orbit

therefore be maintained well below 0.003 for nominal image correction (Reference 2). By performing the postlaunch maneuvers (required to achieve mission orbit altitude and groundtrack phasing) at the optimum location, a near-frozen orbit can be reached. Once the initial target frozen orbit is reached, $\bar{e}$ and $\bar{\omega}$ can be controlled to some extent as part of the routine orbit maintenance maneuvers (which are required to counteract the effects of atmospheric drag) without additional fuel requirements. Targeting toward the frozen orbit was done during the postlaunch injection error removal maneuver sequence for Landsat-5, as discussed in Section 3.

2.3 PHASING WITH LANDSAT-4

Landsat-4 and Landsat-5 both have a repeating groundtrack every 233 revolutions (16 days). Figure 2-3 represents a one-revolution segment of the Equator that contains 16 WRS intervals. Each dot on the Equator represents a WRS longitude point. The number over each WRS longitude shows the day in the 16-day repeat cycle when a Landsat spacecraft in a nominal mission orbit would cross (from north to south) the WRS point. Day 0 of the 16-day repeat cycle was arbitrarily chosen.

The nominal mission orbits of Landsat-4 and Landsat-5 are identical except for their phasing. Landsat-5 is required to be phased with Landsat-4 such that full Earth coverage is provided every 8 days. The 8-day full Earth coverage cycle is achieved when the Landsat spacecraft are 180 degrees apart when in the same orbital plane, as shown in Figure 2-4. This phasing configuration also minimizes interference between the two satellites. Figure 2-5 contrasts the days of coverage in the 16-day cycle for a segment of the Equator for Landsat-4 and Landsat-5. The figure depicts Landsat-5 as being correctly phased eight WRS intervals from Landsat-4, thus providing full coverage every 8 days.

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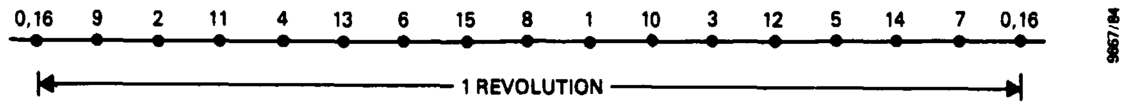

Figure 2-3. WRS Longitude Points and the 16-Day Coverage Cycle

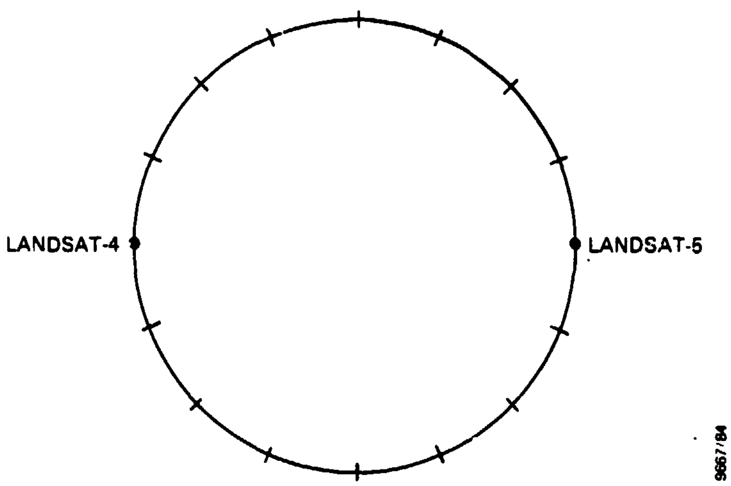

Figure 2-4. Proper Landsat-5 Phasing With Landsat-4 for Full Earth Coverage Every 8 Days

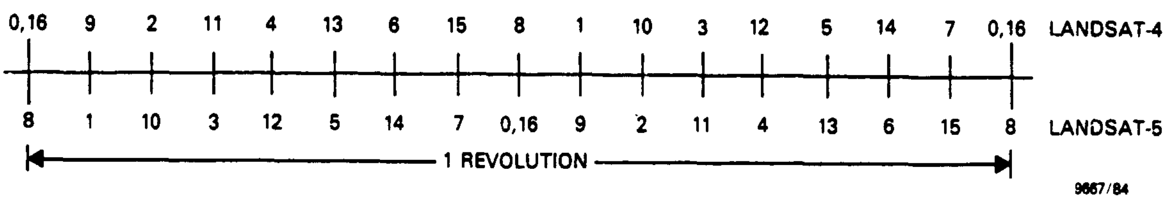

Figure 2-5. Eight-Day Coverage Cycle Between Landsat-4 and Landsat-5

2.4 SOFTWARE FOR MANEUVER PLANNING AND EVALUATION

The software used for Landsat-5 maneuver support consists of programs to perform high-precision orbit propagation, groundtrack monitoring, maneuver targeting, propulsion system modeling, and tracking station coverage prediction. These programs are as follows:

- Goddard Mission Analysis System (GMAS)--The GMAS Cowell propagator is used to generate high-precision ephemeris (EPHEM) files for use by the other programs. The GMAS TRACK module is used to determine groundtrack errors. Averaged orbital elements are generated by the AVECON utility module.

- General Maneuver Program (GMAN)--GMAN performs maneuver targeting, maneuver reconstruction, and propulsion system modeling.

- Groundtrack Monitoring Program (GNDTRAK)--GNDTRAK reads a standard EPHEM file, interpolates to find descending node crossings, and compares the node crossings to the required groundtrack grid. The mean local time of each crossing is also output.

- Circular Orbit Restoration Program (RESTOR)--RESTOR determines maneuver requirements to achieve target values of mean semimajor axis, eccentricity, and argument of perigee. RESTOR was developed for frozen orbit targeting.

- Acquisition Data Program (ACQSCAN)--ACQSCAN determines acquisition- and loss-of-signal (AOS and LOS) times for selected ground stations, determines shadow times, generates various reports, and provides coverage schedules for several Tracking and Data Relay Satellites. ACQSCAN reads a standard EPHEM file.

- Ephemeris File Writer Program (EPHGEN)--EPHGEN contains the same Cowell propagator as GMAS; however, EPHGEN executes in less than 200K bytes of core. The primary output from EPHGEN is a standard EPHEM file.

2.5 PREMANEUVER PLANNING

This subsection discusses the procedures generally followed in planning a typical orbit adjust maneuver and how the software described in the previous subsection is used. The following steps are taken in planning a maneuver:

1. Obtain the latest orbit determination solution (EPHEM tape) or generate an EPHEM file using GMAS or EPHGEN and the latest vector.

2. Run GNDTRAK to check the groundtrack error and determine when a maneuver is necessary to control the groundtrack evolution.

3. Run the GMAS AVECON utility to generate averaged orbital elements at the expected maneuver time.

4. Input averaged elements to RESTOR to determine maneuver location and magnitude required to control orbit semimajor axis, eccentricity, and argument of perigee to the desired values.

5. Run ACQSCAN to determine the best station coverage time for the maneuver (near the location defined by RESTOR).

6. Obtain approval for the requested maneuver date and time.

7. Obtain the latest fuel system temperatures and pressures from the Landsat-5 Control Center.

8. Run GMAN using maneuver magnitude estimates from RESTOR and latest temperatures and pressures to model the maneuver and predict fuel usage.

9. Run the GMAS Cowell propagator and TRACK module with several solar flux level estimates to get a groundtrack evolution prediction.

10. If groundtrack prediction is not satisfactory, change burn duration and repeat steps 8 and 9 as necessary.

Following this analysis, the burn start time and duration are delivered to the control center.

The greatest effect on the groundtrack evolution is from decay of the semimajor axis due to atmospheric drag. Because the solar flux level (which influences atmospheric density at a given altitude) cannot be accurately predicted, it is necessary to use several constant solar flux values (actually, atmospheric density tables) for predicting the effect of a maneuver on the groundtrack. The expected minimum and maximum solar flux levels likely to be encountered during some period following the maneuver are used to estimate bounds for the westward groundtrack drift. The objective is to determine an appropriate burn duration so that the required groundtrack error limits (±10 kilometers) will be maintained in case of sudden changes in the solar flux.

2.6 POSTMANEUVER EVALUATION

Following completion of an orbit adjust maneuver, the following steps are taken to evaluate the propulsion system performance and to calibrate the thruster modeling:

1. Obtain the preburn and postburn orbit determination solution EPHEM tapes; retrieve preburn and postburn state vectors at the same epoch time (burn end time).

2. Convert preburn and postburn vectors to averaged orbital elements using the GMAS AVECON utility and compute the actual change in averaged semimajor axis.

3. Obtain actual temperatures, pressures, and thruster durations observed by the Landsat-5 Control Center.

4. Run GMAN using the observed propulsion system parameters to remodel the burn; this generates a new prediction of orbital changes.

5. Convert predicted postburn osculating elements to averaged elements (AVECON) and compute predicted changes in the orbit.

6. Compare predicted and observed postburn semimajor axis values and compute thruster correction factor.

7. Perform an attitude thruster burn with GMAN using the total observed attitude thruster pulses; this is done to obtain an estimate of fuel used for attitude control.

Following the completion of this procedure, a postburn analysis report is delivered to the control center.
The estimated fuel remaining and thrust correction factor are cataloged for future use.

In evaluating the maneuver with GMAN, several assumptions are made:

- The attitude is held constant at the value originally commanded by the control center (for example, roll, pitch, and yaw = 0.0 degrees). The total attitude thruster counts are used to estimate fuel usage only.

- The burn time used is equal to the total thruster time in milliseconds divided by the number of thrusters used (2 or 4).

For example, GMAN would use a burn time of 251.648 ÷ 4 = 62.912 seconds with four thrusters firing simultaneously, if the observed values for each thruster were as follows:

Thruster	Duration (Milliseconds)
A1	51,648
B1	65,344
C1	67,328
D1	67,328
Total	251,648 (or 251.648 seconds)

Modeling of the Landsat-5 propulsion system, which is identical to the Landsat-4 propulsion system, is described in Reference 4. Since that document was published, an update has been made to the equation for thrust in GMAN to model thruster warmup. The equations used for modeling thrust and specific impulse (I_{SP}) are given below.

$$F = 0.197 + 0.026249P - 0.0000262P^2 \left(\frac{T}{T_S}\right)^{0.03}$$

where F = thrust (pounds)

P = tank pressure (pounds per square inch absolute (psia))

T = current thruster on-time (seconds)

T_S = steady state time (time for thruster to reach full output)

The last term accounts for thruster warmup. The value of T_S used in the GMAN spacecraft data file is 20 seconds. When T becomes greater than T_S, GMAN sets the expression T/T_S equal to 1.

$$I_{SP} = 213.53 + 0.10929P - 0.0001718P^2$$

where I_{SP} = specific impulse (seconds)
P = tank pressure (psia)

The thrust calculated by GMAN can be adjusted by adding a thrust correction factor to the program. The thrust is calculated as noted above and then adjusted as follows:

$$F_{adj} = kF$$

where F = thrust calculated from the polynomial equation
k = thrust correction factor (nominally = 1.0)
F_{adj} = adjusted thrust level

The thrust correction factor for a maneuver is calculated as follows:

$$k_{new} = \left(\frac{\Delta\bar{a}_{obs}}{\Delta\bar{a}_{pre}}\right) k_{old}$$

where Δa_{obs} = observed change in averaged semimajor axis
Δa_{pre} = change in averaged semimajor axis predicted by GMAN
k_{old} = thrust correction factor used by GMAN to generate the prediction

The thrust correction factors for most Landsat-5 maneuvers to date have averaged 0.97 (the observed thrust level has been 97 percent of the nominal thrust predicted by GMAN).

SECTION 3 - LANDSAT-5 MANEUVERS

The Landsat-5 spacecraft was successfully launched into a circular polar orbit on March 1, 1984, by a Delta 3920 launch vehicle that reached an orbit of 12 kilometers below mission altitude. The purpose of the postlaunch maneuver sequence was to raise the semimajor axis the remaining 12 kilometers to the mission altitude, synchronize the groundtrack with the WRS grid, obtain a near-frozen orbit, and phase the spacecraft with Landsat-4 such that an 8-day coverage cycle was obtained between the two satellites. To achieve all these goals, maneuver magnitude and timing were critical. The following subsections discuss details of the postlaunch maneuver sequence and the orbit maintenance maneuvers.

3.1 POSTLAUNCH INJECTION ERROR REMOVAL SEQUENCE

A sequence of eight orbit adjust maneuvers raised the Landsat-5 spacecraft to operational altitude. Three short burns tested the propulsion system in the primary mode (four thrusters) and the backup mode (two thrusters). Five large maneuvers were performed to raise the orbit and synchronize the groundtrack. Details of the maneuvers are presented in Table 3-1. A brief description of the maneuvers is given below.

Maneuver Number	Comments
1	A 5-second burn with two thrusters to test the backup firing mode--This burn produced a semimajor axis change of 197 meters. A large number of attitude thruster firings occurred.
2	A 5-second burn with two thrusters to further test the backup firing mode--A semimajor axis change of 198 meters was achieved.
3	A 16-second burn with four thrusters to test the primary firing mode--The semimajor axis increased by 1.47 kilometers.

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Table 3-1. Postlaunch Injection Error Removal Maneuvers

MANEUVER NUMBER	DAY	ORBIT	DATE (YYMMDD)	TIME (HHMMSS)	NUMBER OF THRUSTERS	DURATION (sec)	LOCATION				WRS TRACK			SEMIMAJOR AXIS CHANGE (km)	ORBITAL PERIOD CHANGE (sec)	HYDRAZINE USED (lb)
							LATITUDE	LONGITUDE	ASC/DSC[a]	STATION	POSITION[b]	DRIFT RATE (km/rev)				
												BEFORE	AFTER			
1	7	83	840307	111703	4	4.608	34.6°S	161.0°E	ASC	ORRORAL	−55.9	+6.9	+6.8	+0.197	+0.25	−0.30
2	9	119	840309	212647	2	4.608	76.5°N	220.2°E	DSC	ALASKA	−60.4	+6.8	+6.6	+0.198	+0.25	−0.21
3	14	192	840314	212803	4	15.888	73.7°N	212.1°E	DSC	ALASKA	+80.7	+6.6	+5.8	+1.473	+1.86	−1.61
4	29	404	840329	110834	4	12.977	34.1°S	183.0°E	ASC	ORRORAL	−61.7	+5.8	+5.1	+1.181	+1.40	−1.28
5	29	405	840329	124854	3	30.336	38.0°S	130.8°E	ASC	ORRORAL	−56.8	+5.1	+3.8	+2.306	+2.80	−2.52
6	30	425	840330	214803	2	40.928	17.1°S	0.3°E	ASC	ASCENSION	+18.4	+3.8	+2.7	+1.863	+2.34	−1.97
7	33	469	840402	205004	2	58.432	33.5°N	6.8°E	ASC	MADRID	−38.0	+2.7	+1.1	+2.636	+3.31	−2.77
8	35	498	840404	203807	2	43.168	38.1°N	8.5°E	ASC	MADRID	−4.9	+1.1	+0.03	+1.900	+2.40	−2.01

[a]ASC = ASCENDING STATION PASS (SOUTH TO NORTH); DSC = DESCENDING STATION PASS (NORTH TO SOUTH).
[b]+ = EAST; − = WEST.

Maneuver Number	Comments
4	A 13-second burn with four thrusters to begin the groundtrack phasing sequence--This burn produced a change in semimajor axis of 1.19 kilometers and slowed the groundtrack drift rate from 5.8 kilometers per revolution to 5.1 kilometers per revolution. The D translational thruster ceased firing during this maneuver, causing excessive off-pulsing. The onboard timer terminated the burn after 102 seconds elapsed. The planned burn duration for this burn was 51 seconds.
5	A 30-second burn performed one orbit after maneuver 4--The burn was designed to complete the planned burn duration of 51 seconds started in maneuver 4. The burn used the primary firing mode, but only three thrusters fired. The semimajor axis was raised by 2.3 kilometers, and the groundtrack drift rate was slowed to 3.8 kilometers per revolution.
6	A 41-second burn with two thrusters--This burn raised the semimajor axis 1.9 kilometers and slowed the groundtrack drift rate to 2.7 kilometers per revolution.
7	A 58-second burn using two thrusters--This burn slowed the groundtrack drift rate to 1.1 kilometers per revolution and raised the semimajor axis by 2.6 kilometers.
8	A 43-second burn with two thrusters--This burn raised the orbit by 1.9 kilometers, phased the spacecraft half an orbital period ahead of Landsat-4, and positioned Landsat-5 into a frozen orbit. The drift rate of the groundtrack was slowed to 0.03 kilometer per revolution.

Following maneuver 8, the groundtrack position was approximately 4.6 kilometers west of the required WRS path (well within the ±10 kilometer limits) and drifting eastward at approximately 0.44 kilometer per day. The fuel use estimated by GMAN for these eight burns is 12.6 pounds.

Table 3-2 presents the predicted and actual changes in averaged semimajor axis for each maneuver and also the calculated thrust correction factors.

Table 3-2. Predicted and Actual Changes in Averaged Semimajor Axis

MANEUVER	PREBURN $\bar{a}$[a]	PREDICTED POSTBURN $\bar{a}$	OBSERVED POSTBURN $\bar{a}$	PREDICTED $\Delta\bar{a}$	OBSERVED $\Delta\bar{a}$	THRUST CORRECTION FACTOR
1	7066.0868	7066.2950	7066.2837	0.2082	0.1969	0.9457
2	7066.2883	7066.4960	7066.4864	0.2077	0.1981	0.9538
3	7066.4749	7067.9243	7067.9478	1.4494	1.4729	0.9959
4	7067.8908	7069.0830	7069.0816	1.1922	1.1908	0.9988
5	7069.0767	7071.2072	7071.3814	2.1305	2.3047	1.0821
6	7071.3692	7073.2814	7073.2318	1.9122	1.8626	0.9739
7	7073.2325	7075.9524	7075.8673	2.7199	2.6348	0.9686
8	7075.8637	7077.7872	7077.7722	1.9235	1.9085	0.9624

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[a]BOTH PREBURN AND POSTBURN VALUES ARE ONE-ORBIT NUMERICAL AVERAGES AT EPOCH OF BURNOUT FOR EACH MANEUVER. ALL VALUES ARE IN KILOMETERS.

The evolution of the Landsat-5 groundtrack through the post-launch injection error removal period is illustrated in Figure 3-1. The groundtrack grid comprises 233 equatorial crossings that are 172 kilometers apart. At each descending node crossing, the groundtrack is compared to the nearest grid line. The maximum groundtrack error is then half the distance between lines, or 86 kilometers. The initial drift rate in the groundtrack following launch was 100 kilometers per day. The apparently instantaneous changes from positive to negative in the plot of Figure 3-1 indicate that the halfway point between two adjacent grid lines has been crossed and the groundtrack error is then being checked against the next longitude. As maneuvers are performed to raise the semimajor axis, the drift rate decreases. The final burn was performed when the groundtrack error was within the ±10 kilometer bounds.

Figure 3-2 illustrates the evolution of the frozen orbit in terms of $e \cos \omega$ and $e \sin \omega$. The effect of each maneuver on the eccentricity vector can be seen. The appendix contains more details on each maneuver.

Landsat-5 was phased approximately half an orbital period (180 degrees) behind Landsat-4 following separation. The injection orbit of Landsat-5 was 12 kilometers lower in the semimajor axis than that of the Landsat-4 mission orbit. This caused Landsat-5 to gradually catch up to Landsat-4 and then pass it, until Landsat-5 led Landsat-4 by half an orbital period. Orbit adjust maneuver 8 was then executed to complete the injection error removal sequence, correctly phasing Landsat-5 180 degrees from Landsat-4 to provide an 8-day full Earth coverage cycle. Figure 3-3 depicts the phasing evolution between Landsat-4 and Landsat-5 during the injection error removal sequence of Landsat-5. The phasing is measured by comparing the times of corresponding

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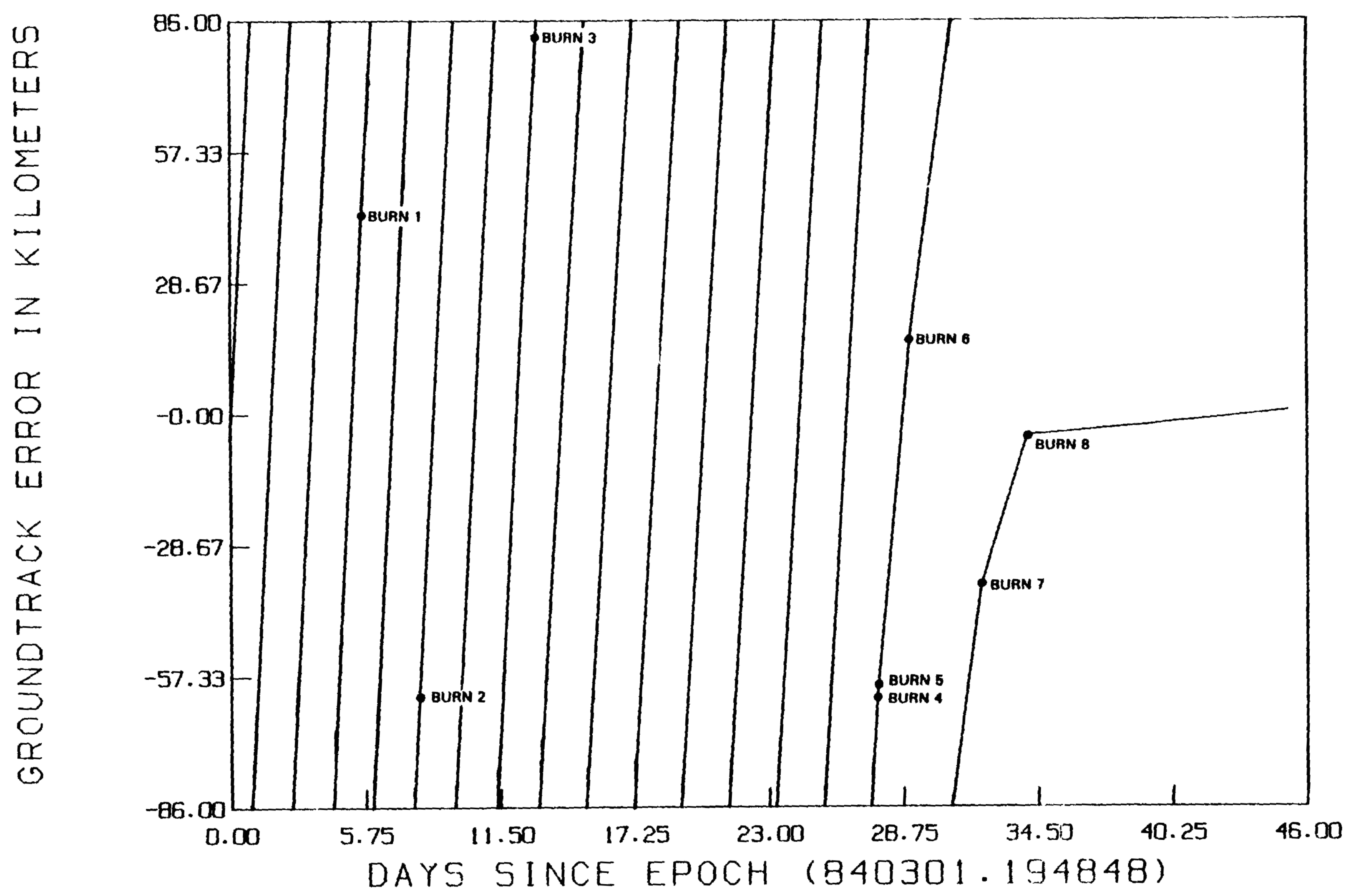

Figure 3-1. Groundtrack Evolution During Postlaunch Injection Error Removal

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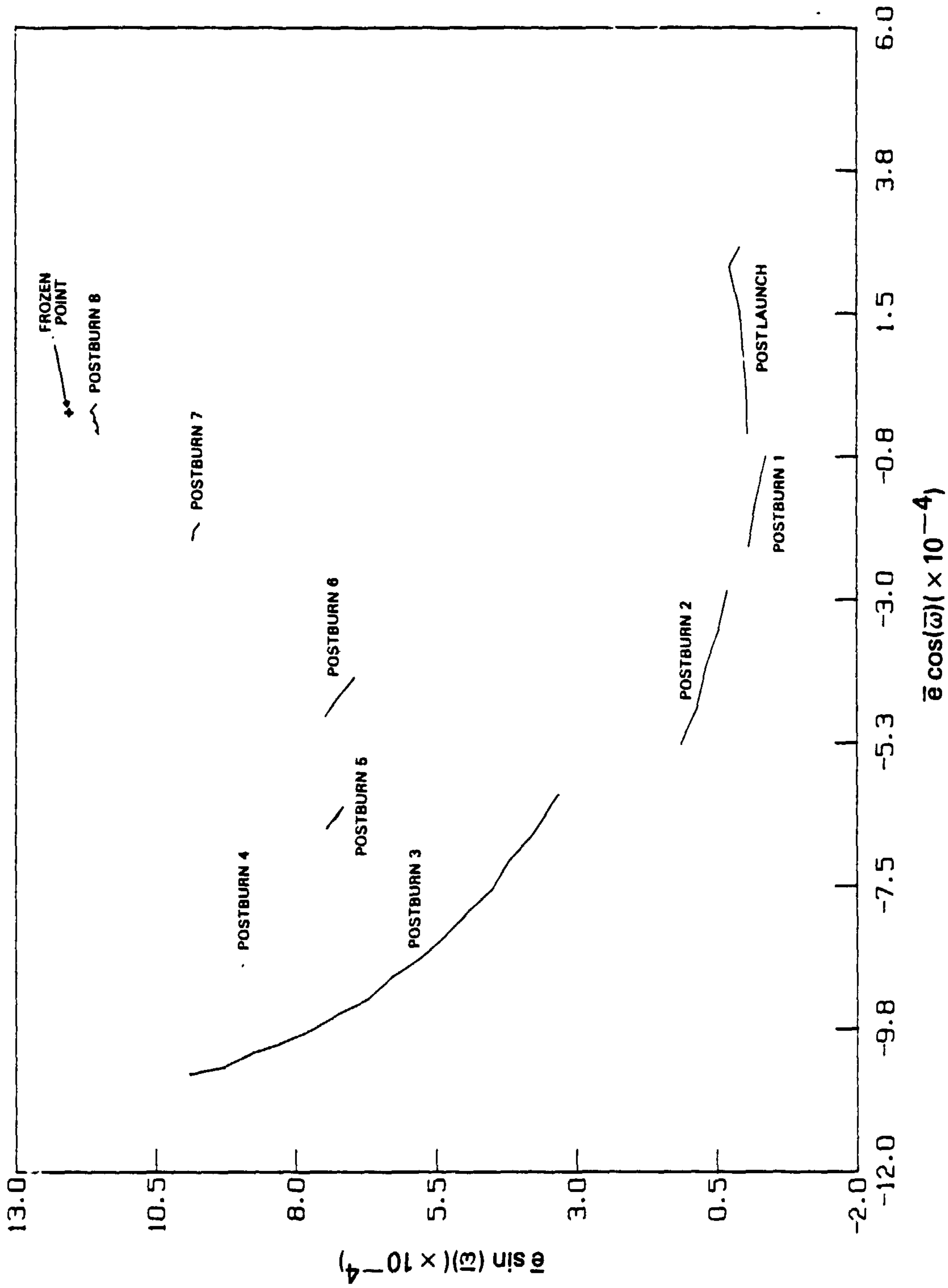

Figure 3-2. Frozen Orbit Evolution During Postlaunch Injection Error Removal

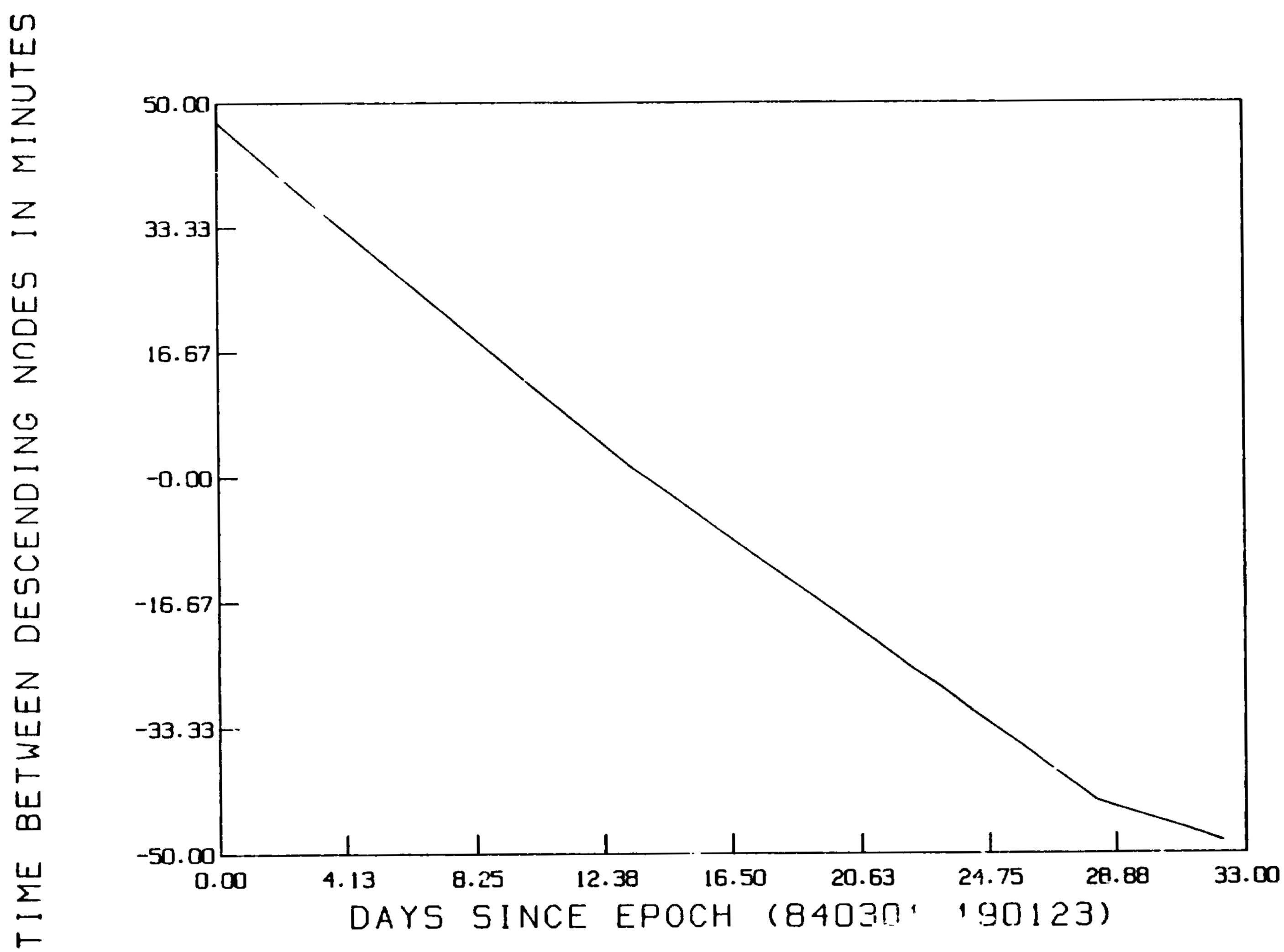

Figure 3-3. Phasing Evolution Between Landsat-4 and Landsat-5 During the Landsat-5 Injection Error Removal Sequence

descending nodal crossings of the two Landsat spacecraft. A positive value in the time difference indicates that Landsat-4 is leading Landsat-5. Landsat-5 leads Landsat-4 when the value is negative.

3.2 ORBIT AND GROUNDTRACK MAINTENANCE MANEUVERS

Following launch and initial groundtrack phasing maneuvers, orbit control for the Landsat-5 spacecraft entered the orbit maintenance phase. The objective of orbit maintenance is to control the spacecraft altitude within the range that will confine the groundtrack to within 10 kilometers east or west of the required WRS path. This is accomplished by periodic adjustments to the semimajor axis on the order of 100 to 300 meters. The rate of semimajor axis decay, and thus the period between maintenance maneuvers, depends on the solar flux level. The targeted change in semimajor axis will depend on the estimated level of solar activity for several months following the maneuver.

Figure 3-4 illustrates the predicted effect of a typical maneuver on groundtrack error depending on the average solar flux level encountered (solar flux is given in units of 10^{-22} watts per square meter per hertz and is for a 10.7-centimeter wavelength). Following a maneuver, the groundtrack begins drifting westward. The objective of the maneuver is to force the groundtrack to drift to the western boundary (-10 kilometers), turn around, and drift eastward. As the groundtrack reaches the eastern boundary (+10 kilometers), another maintenance burn is required to reverse the drift. If the solar flux level suddenly drops below the predicted average soon after the maneuver, the groundtrack may cross the western boundary. To correct at this point would require a retrograde maneuver (180-degree spacecraft yaw). Because this is undesirable from a spacecraft operational standpoint, it is necessary to be conservative in

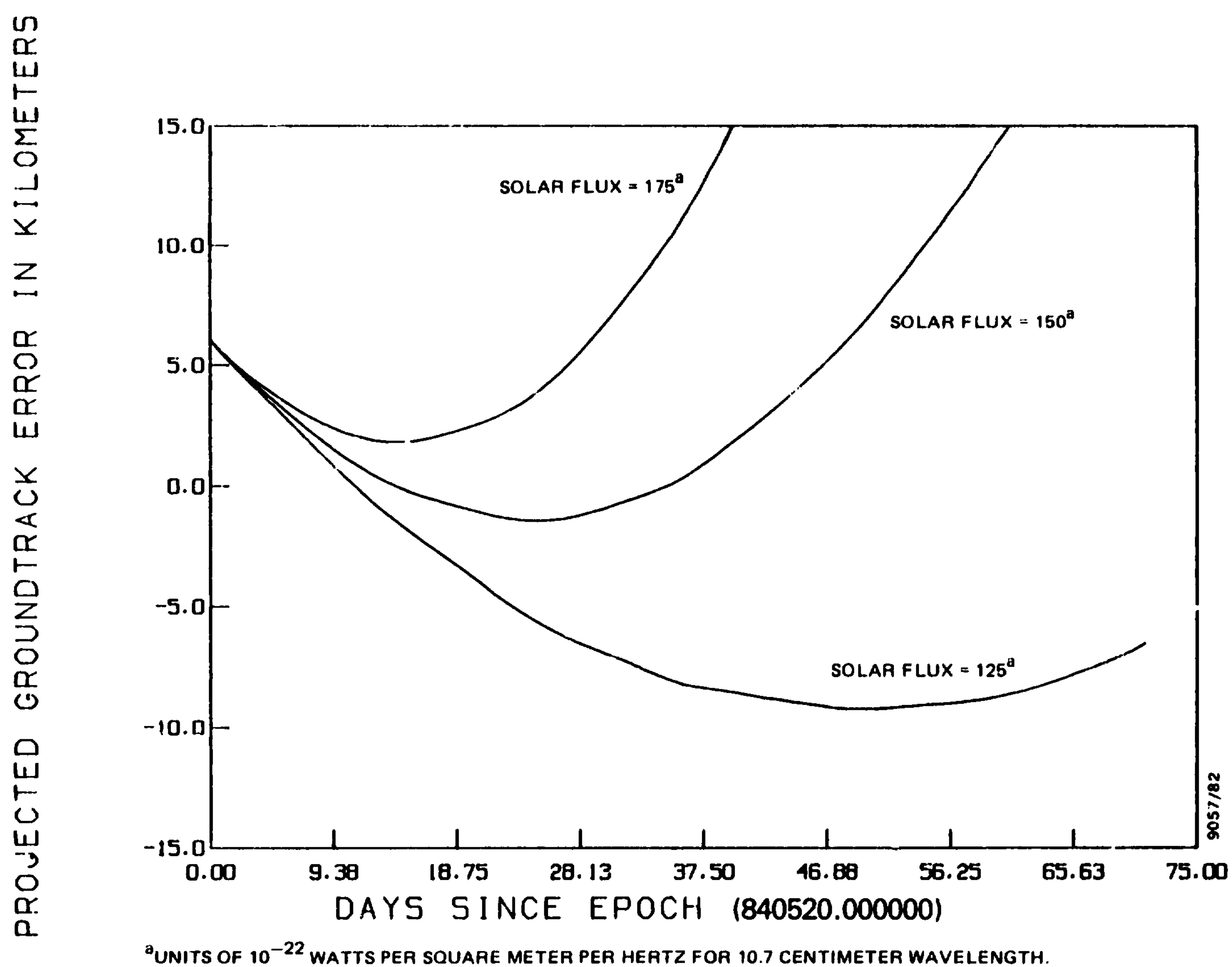

Figure 3-4. Effect of Solar Flux Level on Postmaneuver Groundtrack Evolution

estimating maneuver magnitude. The minimum burn length obtainable with the Landsat-5 propulsion module is 256 milliseconds with two thrusters firing simultaneously. This translates into a change in the semimajor axis of approximately 11 meters, which can make a difference of several kilometers in the westward groundtrack drift (depending on solar activity). The lower the solar flux encountered, the greater the difference in westward drift produced by two burns differing by one 256-millisecond pulse. Therefore, in planning the maneuver, the lowest expected average solar flux is used to define an upper limit for the burn time. Initial estimates of future solar activity are taken from predictions made by the Marshall Space Flight Center. The maintenance burns will be inserted in the appendix as they occur, beginning with maneuver 9.

In addition to controlling the groundtrack, the mean local time of the descending node must be maintained between 9:30 and 10:00 a.m. The local time is affected by the nodal regression rate, which is determined by the inclination of the orbit. Because the inclination changes slowly in time due to the gravitational effects of the Sun and Moon, the nodal rate will change causing a change in local ti... Inclination change maneuvers are required to restore the Sun-synchronous node rate. The inclination produced by the Delta 3920 launch vehicle was biased in such a way as to allow a relatively long time from launch to the first inclination change maneuver. It is expected that this maneuver will be required approximately 18 months after launch. During the life of the mission, detailed analysis will be performed to determine the exact date. Additional maneuvers may be required at 8-month intervals thereafter. The change in inclination for each burn is expected to be on the order of 0.05 degree. The mean local time of the descending node at injection was at 9:38 a.m.

APPENDIX - LANDSAT-5 ORBIT ADJUST MANEUVER DATA

This appendix contains data and analysis results for all maneuvers performed to date. It is intended that new tables and figures will be produced as additional maneuvers are performed. For each maneuver, the following two tables and two figures are provided:

- Table of orbit parameters for the given maneuver
- Table of spacecraft propulsion system parameters
- Plot of observed groundtrack since the previous maneuver
- Plot of observed mean local time of the descending node since the previous maneuver

Table A-1. Orbit Parameters for Maneuver 1

MANEUVER 1	ORBIT 83	DATE 840307	BURN START TIME (GMT) 111703	
OSCULATING ELEMENTS[a]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	
a	7069.3127	7069.5209	7069.5100	
e	0.0005666	0.0005532	0.0005561	
i	98.2528466	98.2528614	98.2528714	
Ω	129.90767	129.90766	129.90768	
ω	203.27405	205.98180	205.90883	
M	121.98106	119.29310	119.34712	
EPOCH (YYMMDD)	8403C.'	840307	840307	
(HHMMSS)	111707.608	111707.608	111707.608	
AVERAGED ELEMENTS[b]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	CHANGE (OBSERVED – PREBURN)
$\bar{a}$	7066.0868	7066.2950	7066.2837	0.1969
$\bar{e}$	0.0000974	0.0000811	0.0000841	–0.0000133
$\bar{i}$	98.2549317	98.2549465	98.2549567	0.0000250
$\bar{\Omega}$	129.90258	129.90257	129.90259	0.00001
$\bar{\omega}$	190.62922	206.52258	206.12131	15.49209
$\bar{M}$	134.67859	118.78501	119.18734	–15.49125
EPOCH (YYMMDD)	840307	840307	840307	
(HHMMSS)	111707.608	111707.608	111707.608	
PERIOD (sec)	5911.25	5911.51	5911.50	0.25
PERIGEE ALTITUDE[c]	687.2586	687.5819	687.5494	
APOGEE ALTITUDE[c]	688.6350	688.7281	688.7380	
$\bar{e}$ COS $\bar{\omega}$	–0.0000957	–0.0000726	–0.0000756	
$\bar{e}$ SIN $\bar{\omega}$	–0.0000180	–0.0000362	–0.0000370	
GROUNDTRACK ERROR (km)[d]	44.3			
MEAN LOCAL TIME OF DESCENDING NODE (HHMMSS)	093808			

[a] a = SEMIMAJOR AXIS (km)
e = ECCENTRICITY
i = INCLINATION (deg)
Ω = RIGHT ASCENSION OF ASCENDING NODE (deg)
ω = ARGUMENT OF PERIGEE (deg)
M = MEAN ANOMALY (deg)
TIMES ARE GMT

[b] NUMERICALLY AVERAGED OVER ONE ORBIT

[c] EQUATORIAL REFERENCE

[d] DISTANCE EAST (+) OR WEST (–) OF WORLD REFERENCE SYSTEM PATH

9867/54c*1 84

Table A-2. Spacecraft Parameters for Maneuver 1

MANEUVER	ORBIT	DATE	BURN START TIME (GMT)
1	83	840307	111703
SPACECRAFT PARAMETERS		PREBURN	POSTBURN
FUEL SYSTEM PRESSURE (PSIA)		297.48	296.94
TANK TEMPERATURES (°C)			
TANK 1		17.11	17.11
TANK 2		16.61	16.61
TANK 3		18.18	18.18
TANK 4[a]		16.24	16.24
HYDRAZINE REMAINING (POUNDS)			
TANK 1		55.67	55.61
TANK 2		55.67	55.61
TANK 3		55.67	55.61
TANK 4		343.50	343.36
TOTAL FUEL		510.51	510.19
TOTAL SPACECRAFT WEIGHT		4284.78	4284.46
THRUSTERS			
ORBIT ADJUST THRUSTERS USED			B1, D1
TOTAL ORBIT ADJUST THRUSTER DURATION (sec)[b]			9.216
TOTAL ATTITUDE THRUSTER DURATION (sec)			102.080
SPACECRAFT ATTITUDE (deg)[c]			
PITCH			0.0
YAW			0.0
ROLL			0.0
MANEUVER CALIBRATION			
SEMIMAJOR AXIS CHANGE (km)			
PREDICTED			0.2082
OBSERVED			0.1969
INCLINATION CHANGE (deg)			
PREDICTED			N/A
OBSERVED			N/A
THRUST CORRECTION FACTOR			
USED FOR PLANNING			1.0000
RECALIBRATED[d]			0.9457

9667(54*)/84

[a]TANK 4 IS THE AUXILLIARY TANK KIT (ATK)

[b]BURN TIME INPUT TO GENERAL MANEUVER PROGRAM (GMAN) = TOTAL DURATION ÷ NUMBER OF THRUSTERS

[c]SPACECRAFT ATTITUDE AS INPUT TO GMAN FOR MANEUVER MODELING

[d]RECALIBRATED THRUST CORRECTION FACTOR = (OBSERVED ÷ PREDICTED) × FACTOR USED FOR PLANNING

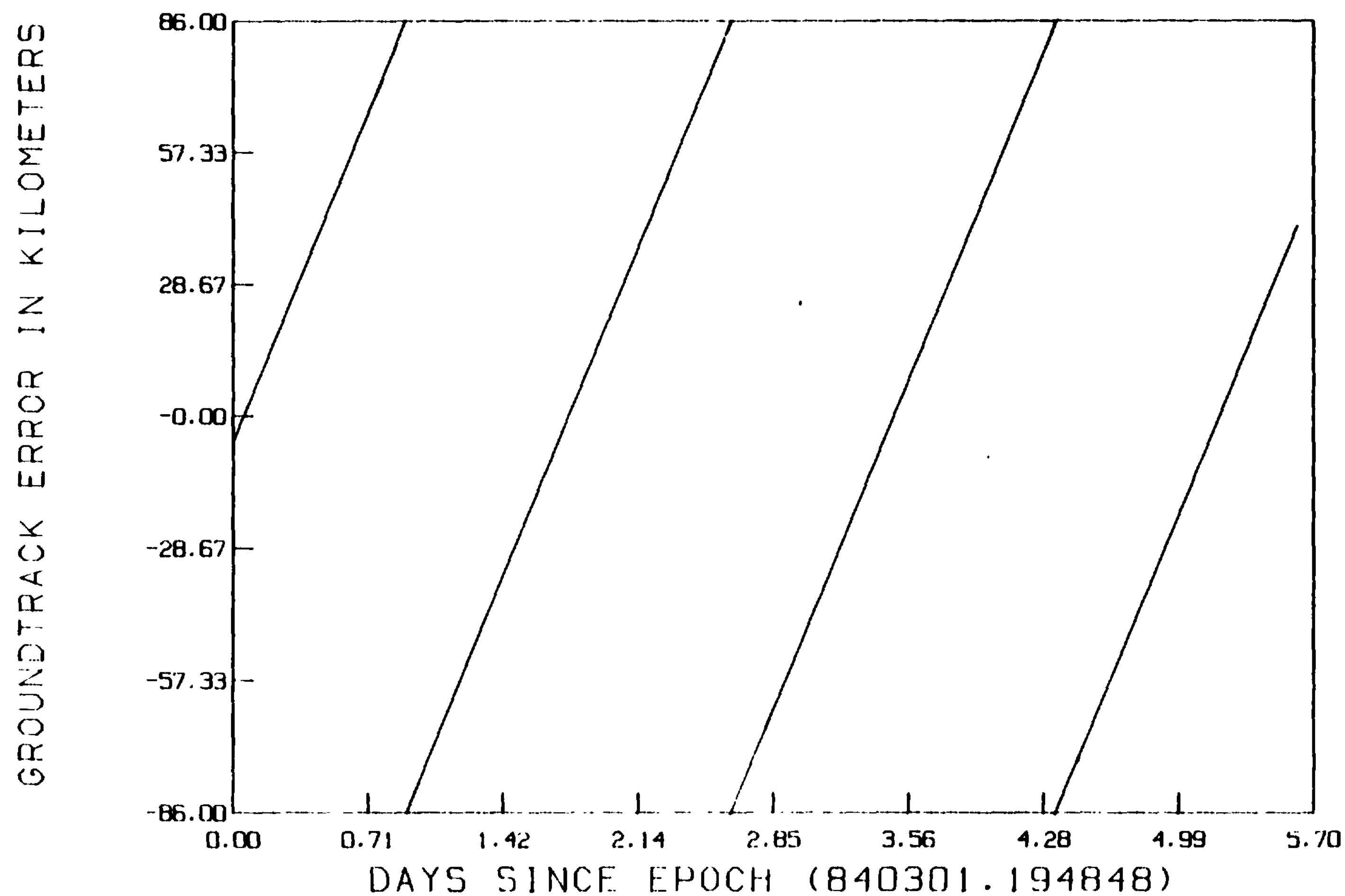

Figure A-1. Groundtrack Evolution Between Launch and Maneuver 1

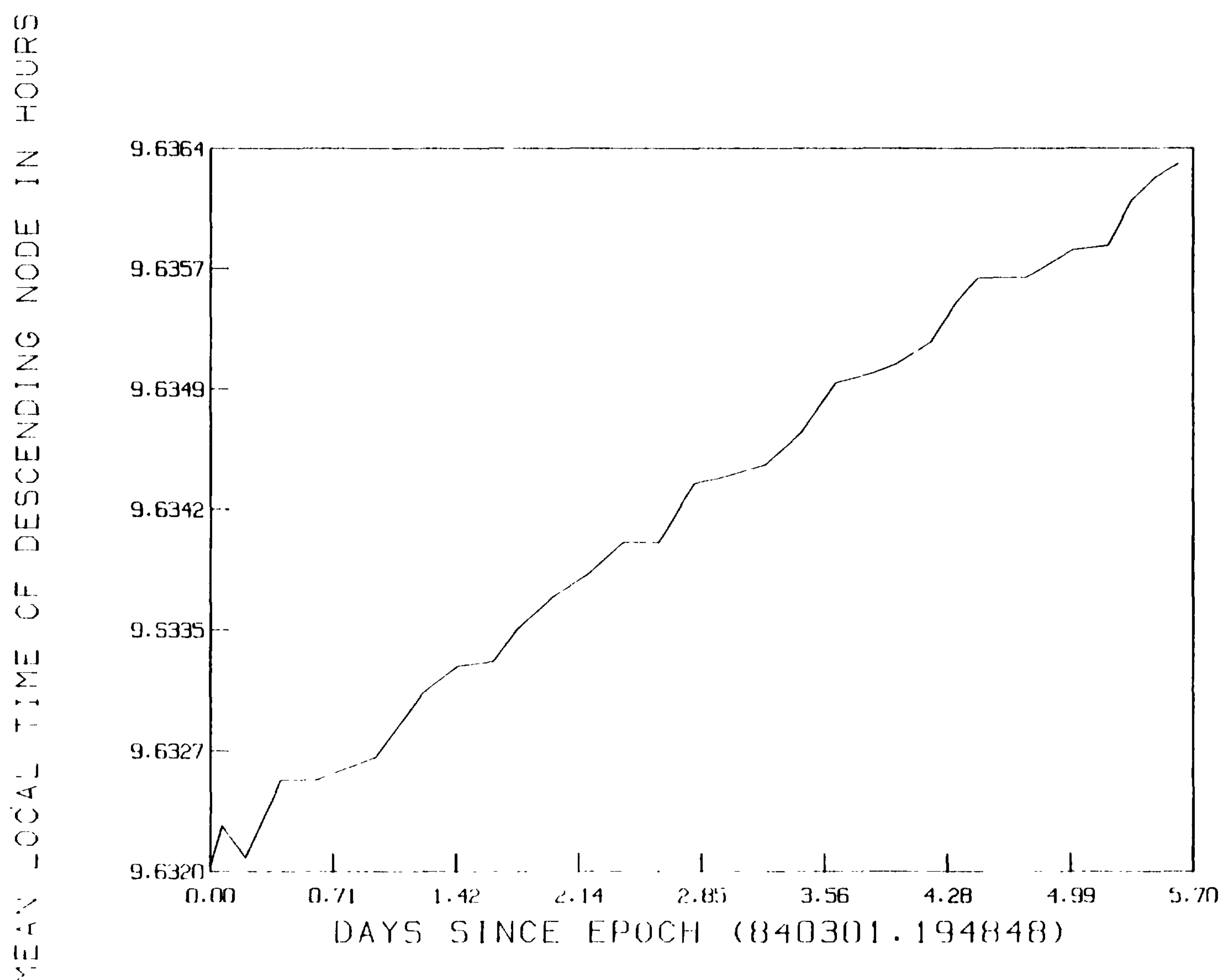

Figure A-2. Mean Local Time of Descending Node Between Launch and Maneuver 1

Table A-3. Orbit Parameters for Maneuver 2

MANEUVER 2	ORBIT 119	DATE 840309	BURN START TIME (GMT) 212647	
OSCULATING ELEMENTS[a]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	
a	7057.7848	7057.9918	7057.9823	
e	0.0015745	0.0015451	0.0015466	
i	98.2598628	98.2598594	98.2599719	
Ω	132.31968	132.31970	132.31973	
ω	277.30691	277.30452	277.25790	
M	183.67218	183.67437	183.72113	
EPOCH (YYMMDD)	840309	840309	840309	
(HHMMSS)	212651.608	212651.608	212651.608	
AVERAGED ELEMENTS[b]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	CHANGE (OBSERVED – PREBURN)
$\bar{a}$	7066.2883	7066.4960	7066.4864	0.1981
$\bar{e}$	0.0002603	0.0002649	0.0002658	0.0000055
$\bar{i}$	98.2548722	98.2548689	98.2549813	0.0001091
$\bar{\Omega}$	132.31767	132.31769	132.31773	0.00006
$\bar{\omega}$	181.60596	175.20228	175.[illegible]2668	–5.97928
$\bar{M}$	279.39296	285.73644	285.37219	5.97923
EPOCH (YYMMDD)	840309	840309	840309	
(HHMMSS)	212651.608	212651.608	212651.608	
PERIOD (sec)	5911.50	5911.76	5911.75	0.25
PERIGEE ALTITUDE[c]	686.3089	686.4841	686.4681	
APOGEE ALTITUDE[c]	689.9877	690.2279	690.2247	
$\bar{e}$ COS $\bar{\omega}$	–0.0002602	–0.0002640	–0.0002650	
$\bar{e}$ SIN $\bar{\omega}$	–0.0000073	0.0000219	0.0000203	
GROUNDTRACK ERROR (km)[d]	–60.4			
MEAN LOCAL TIME OF DESCENDING NODE (HHMMSS)	093817			

9867(54*)/84

[a] a = SEMIMAJOR AXIS (km)
e = ECCENTRICITY
i = INCLINATION (deg)
Ω = RIGHT ASCENSION OF ASCENDING NODE (deg)
ω = ARGUMENT OF PERIGEE (deg)
M = MEAN ANOMALY (deg)
TIMES ARE GMT

[b] NUMERICALLY AVERAGED OVER ONE ORBIT

[c] EQUATORIAL REFERENCE

[d] DISTANCE EAST (+) OR WEST (–) OF WORLD REFERENCE SYSTEM PATH

Table A-4. Spacecraft Parameters for Maneuver 2

MANEUVER	ORBIT	DATE	BURN START TIME (GMT)
2	119	840309	212647

SPACECRAFT PARAMETERS	PREBURN	POSTBURN
FUEL SYSTEM PRESSURE (PSIA)	296.97	296.61
TANK TEMPERATURES (°C)		
TANK 1	17.47	17.47
TANK 2	17.11	17.11
TANK 3	18.71	18.71
TANK 4[a]	16.23	16.23
HYDRAZINE REMAINING (POUNDS)		
TANK 1	55.61	55.57
TANK 2	55.61	55.57
TANK 3	55.61	55.57
TANK 4	343.36	343.26
TOTAL FUEL	510.19	509.97
TOTAL SPACECRAFT WEIGHT	4284.46	4284.24

THRUSTERS	
ORBIT ADJUST THRUSTERS USED	B1, D1
TOTAL ORBIT ADJUST THRUSTER DURATION (sec)[b]	9.216
TOTAL ATTITUDE THRUSTER DURATION (sec)	7.840
SPACECRAFT ATTITUDE (deg)[c]	
PITCH	0.0
YAW	0.0
ROLL	0.0
MANEUVER CALIBRATION	
SEMIMAJOR AXIS CHANGE (km)	
PREDICTED	0.2077
OBSERVED	0.1981
INCLINATION CHANGE (deg)	
PREDICTED	N/A
OBSERVED	N/A
THRUST CORRECTION FACTOR	
USED FOR PLANNING	1.0000
RECALIBRATED[d]	0.9538

9667(54*)/84

[a]TANK 4 IS THE AUXILLIARY TANK KIT (ATK)

[b]BURN TIME INPUT TO GENERAL MANEUVER PROGRAM (GMAN) = TOTAL DURATION ÷ NUMBER OF THRUSTERS

[c]SPACECRAFT ATTITUDE AS INPUT TO GMAN FOR MANEUVER MODELING

[d]RECALIBRATED THRUST CORRECTION FACTOR = (OBSERVED ÷ PREDICTED) × FACTOR USED FOR PLANNING

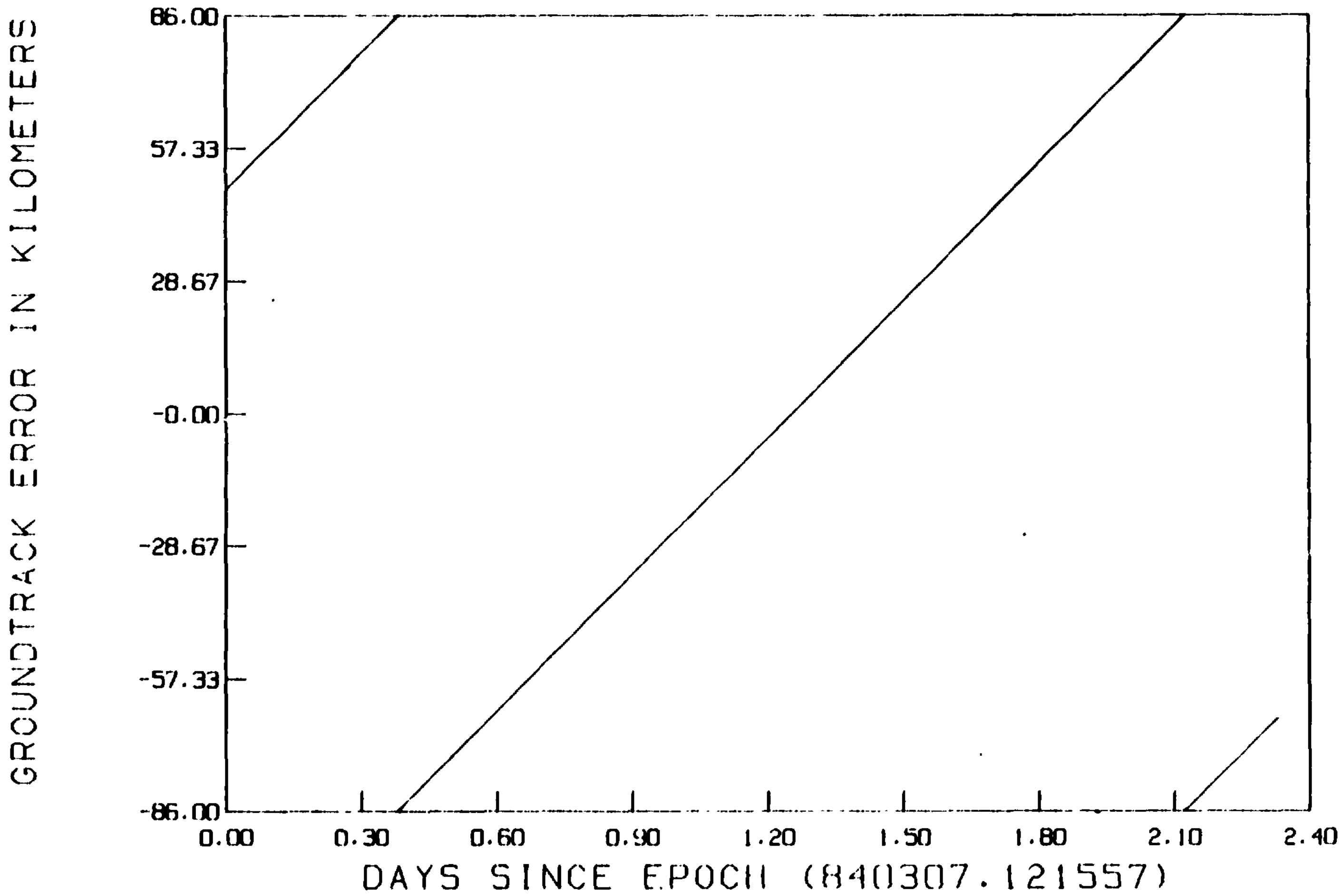

Figure A-3. Groundtrack Evolution Between Maneuvers 1 and 2

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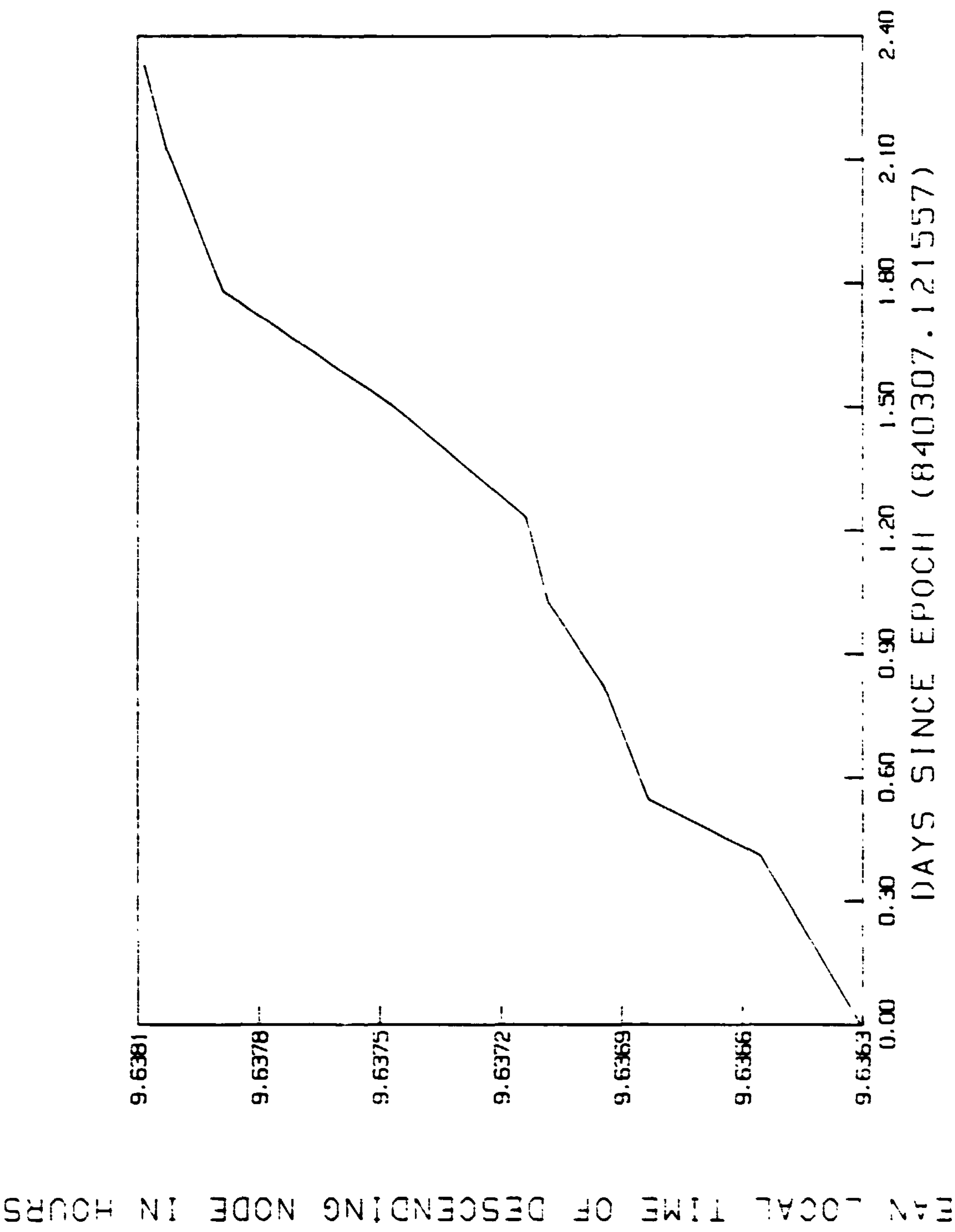

Figure A-4. Mean Local Time of Descending Node Between Maneuvers 1 and 2

Table A-5. Orbit Parameters for Maneuver 3

MANEUVER 3	ORBIT 192	DATE 840314	BURN START TIME (GMT) 212903	
OSCULATING ELEMENTS[a]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	
a	7058.5342	7059.9786	7060.0020	
e	0.0013113	0.0011094	0.0011060	
i	98.2595169	98.2594774	98.2595338	
Ω	137.30470	137.30485	137.30499	
ω	271.67404	269.91821	269.90158	
M	193.41979	195.17410	195.19068	
EPOCH (YYMMDD)	840314	840314	840314	
(HHMMSS)	212918.888	212918.888	212918.888	
AVERAGED ELEMENTS[b]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	CHANGE (OBSERVED – PREBURN)
$\bar{a}$	7066.4749	7067.9243	7067.9478	1.4729
$\bar{e}$	0.0005825	0.0006916	0.0006935	0.0001110
$\bar{i}$	98.2548668	98.2548279	98.2548843	0.0000175
$\bar{\Omega}$	137.30203	137.30218	137.30232	0.00029
$\bar{\omega}$	167.29515	151.55642	151.32066	– 15.97449
$\bar{M}$	297.82554	313.56275	313.79847	15.97293
EPOCH (YYMMDD)	840314	840314	840314	
(HHMMSS)	212918.888	212918.888	212918.888	
PERIOD (sec)	5911.74	5913.56	5913.59	1.85
PERIGEE ALTITUDE[c]	684.2187	684.8961	684.9062	
APOGEE ALTITUDE[c]	692.4511	694.6725	694.7094	
$\bar{e}$ COS $\bar{\omega}$	–0.0005682	–0.0006081	–0.0006084	
$\bar{e}$ SIN $\bar{\omega}$	0.0001281	0.0003294	0.0003328	
GROUNDTRACK ERROR (km)[d]	80.7			
MEAN LOCAL TIME OF DESCENDING NODE (HHMMSS)	093830			

9667(54*)/84

[a] a = SEMIMAJOR AXIS (km)
e = ECCENTRICITY
i = INCLINATION (deg)
Ω = RIGHT ASCENSION OF ASCENDING NODE (deg)
ω = ARGUMENT OF PERIGEE (deg)
M = MEAN ANOMALY (deg)
TIMES ARE GMT

[b] NUMERICALLY AVERAGED OVER ONE ORBIT

[c] EQUATORIAL REFERENCE

[d] DISTANCE EAST (+) OR WEST (–) OF WORLD REFERENCE SYSTEM PATH

Table A-6. Spacecraft Parameters for Maneuver 3

MANEUVER	ORBIT	DATE	BURN START TIME (GMT)
3	192	840314	212903
SPACECRAFT PARAMETERS		PREBURN	POSTBURN
FUEL SYSTEM PRESSURE (PSIA)		295.12	292.49
TANK TEMPERATURES (°C)			
TANK 1		17.28	17.28
TANK 2		16.74	16.74
TANK 3		18.52	18.52
TANK 4[a]		15.58	15.58
HYDRAZINE REMAINING (POUNDS)			
TANK 1		55.57	55.30
TANK 2		55.57	55.30
TANK 3		55.57	55.30
TANK 4		343.26	342.57
TOTAL FUEL		509.97	508.47
TOTAL SPACECRAFT WEIGHT		4284.24	4282.74

THRUSTERS	
ORBIT ADJUST THRUSTERS USED	A1, B1, C1, D1
TOTAL ORBIT ADJUST THRUSTER DURATION (sec)[b]	63.552
TOTAL ATTITUDE THRUSTER DURATION (sec)	17.080
SPACECRAFT ATTITUDE (deg)[c]	
PITCH	0.0
YAW	0.0
ROLL	0.0
MANEUVER CALIBRATION	
SEMIMAJOR AXIS CHANGE (km)	
PREDICTED	1.4494
OBSERVED	1.4729
INCLINATION CHANGE (deg)	
PREDICTED	N/A
OBSERVED	N/A
THRUST CORRECTION FACTOR	
USED FOR PLANNING	0.9800
RECALIBRATED[d]	0.9959

9667(54a*)1/84

[a] TANK 4 IS THE AUXILIARY TANK KIT (ATK)

[b] BURN TIME INPUT TO GENERAL MANEUVER PROGRAM (GMAN) = TOTAL DURATION ÷ NUMBER OF THRUSTERS

[c] SPACECRAFT ATTITUDE AS INPUT TO GMAN FOR MANEUVER MODELING

[d] RECALIBRATED THRUST CORRECTION FACTOR = (OBSERVED ÷ PREDICTED) × FACTOR USED FOR PLANNING

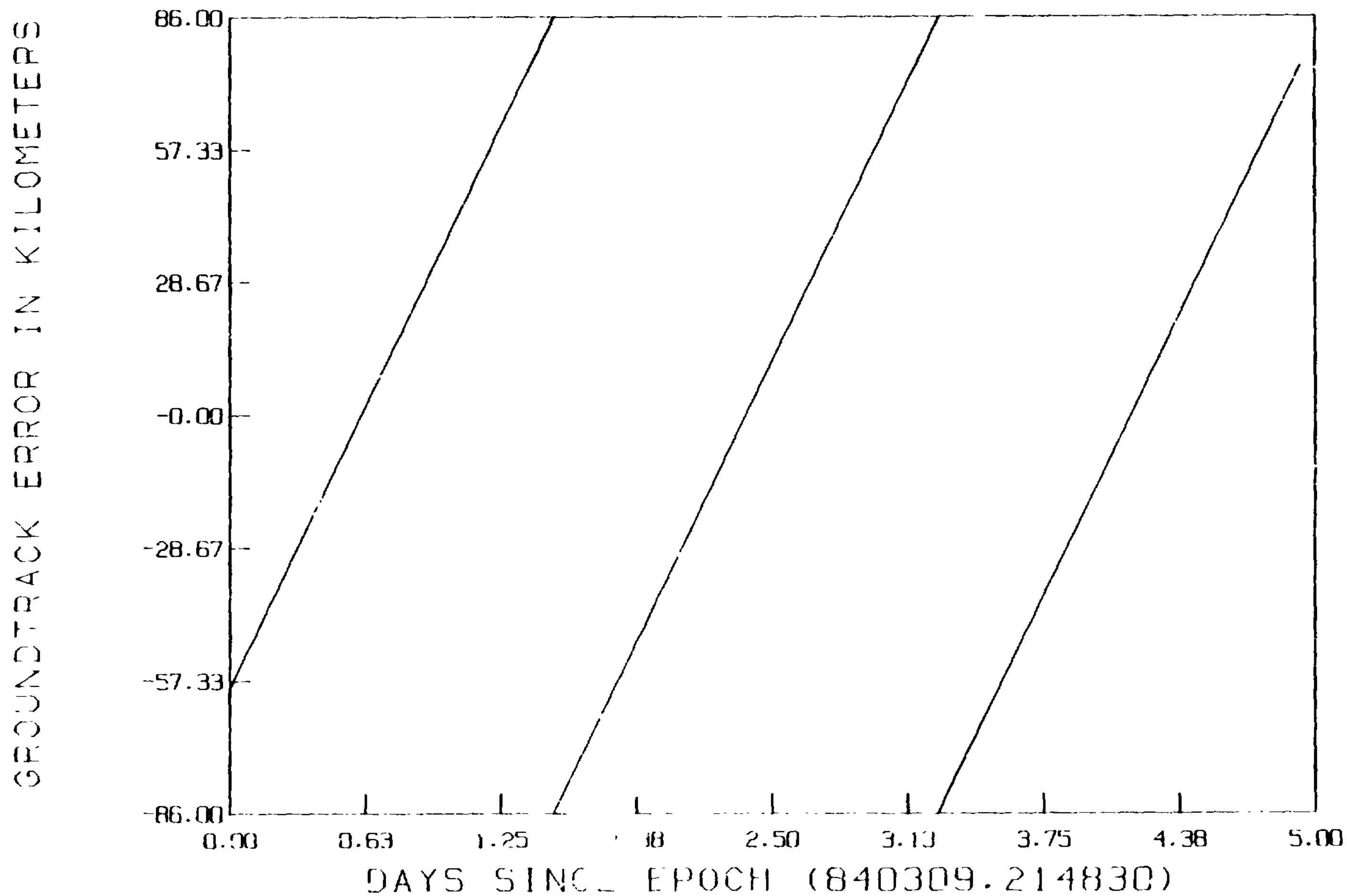

Figure A-5. Groundtrack Evolution Between Maneuvers 2 and 3

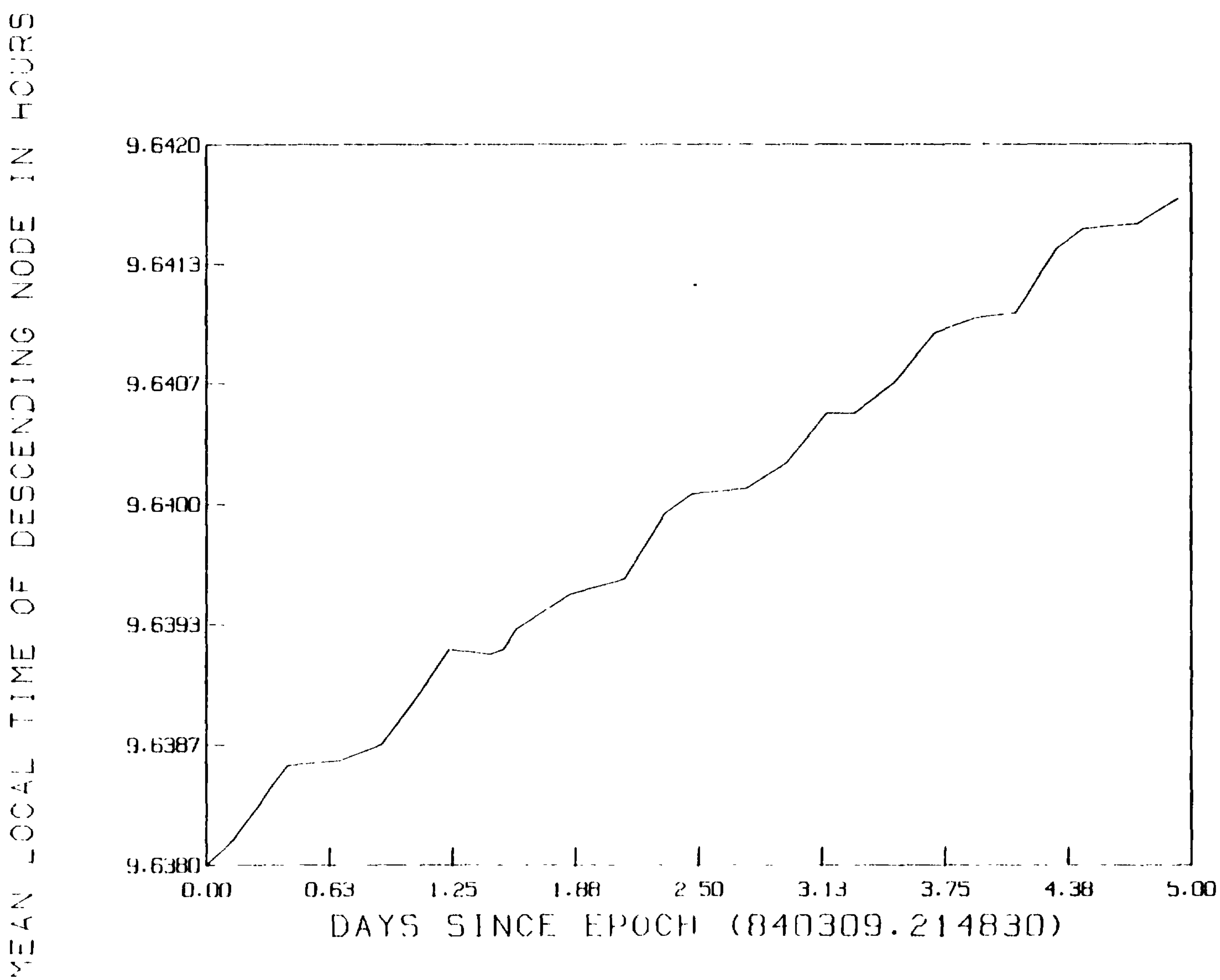

Figure A-6. Mean Local Time of Descending Node Between Ma uvers 2 and 3

Table A-7. Orbit Parameters for Maneuver 4

MANEUVER 4	ORBIT 404	DATE 840329	BURN START TIME (GMT) 110934	
OSCULATING ELEMENTS[a]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	
a	7071.3944	7072.5863	7072.5850	
e	0.0016011	0.0014342	0.0014319	
i	98.2493759	98.2494846	98.2497870	
Ω	151.81186	151.81179	151.81153	
ω	151.24106	152.27330	152.10650	
M	174.97705	173.94356	174.11100	
EPOCH (YYMMDD)	840329	840329	840329	
(HHMMSS)	110946.977	110946.977	110946.977	
AVERAGED ELEMENTS[b]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	CHANGE (OBSERVED – PREBURN)
$\bar{a}$	7067.8908	7069.0830	7069.0816	1.1908
$\bar{e}$	0.0014209	0.0012533	0.0012524	−0.0001685
$\bar{i}$	98.2516450	98.2517534	98.2520559	0.0004109
$\bar{\Omega}$	151.80685	151.80678	151.80653	−0.00032
$\bar{\omega}$	135.52514	134.59150	134.37762	−1.14752
$\bar{M}$	190.74478	191.67715	191.89168	1.14690
EPOCH (YYMMDD)	840329	840329	840329	
(HHMMSS)	110946.977	110946.977	110946.977	
PERIOD (sec)	5913.51	5915.01	5915.01	1.50
PERIGEE ALTITUDE[c]	679.7080	682.0833	682.0883	
APOGEE ALTITUDE[c]	699.7936	699.8027	699.7949	
$\bar{e}$ COS $\bar{\omega}$	−0.0010139	−0.0008799	−0.0008759	
$\bar{e}$ SIN $\bar{\omega}$	0.0009955	0.0008925	0.0008951	
GROUNDTRACK ERROR (km)[d]	−61.7			
MEAN LOCAL TIME OF DESCENDING NODE (HHMMSS)	093905			

9867(54a*)/84

[a] a = SEMIMAJOR AXIS (km)
e = ECCENTRICITY
i = INCLINATION (deg)
Ω = RIGHT ASCENSION OF ASCENDING NODE (deg)
ω = ARGUMENT OF PERIGEE (deg)
M = MEAN ANOMALY (deg)
TIMES ARE GMT

[b] NUMERICALLY AVERAGED OVER ONE ORBIT

[c] EQUATORIAL REFERENCE

[d] DISTANCE EAST (+) OR WEST (−) OF WORLD REFERENCE SYSTEM PATH

Table A-8. Spacecraft Parameters for Maneuver 4

MANEUVER	ORBIT	DATE	BURN START TIME (GMT)
4	404	840329	110934
SPACECRAFT PARAMETERS		PREBURN	POSTBURN
FUEL SYSTEM PRESSURE (PSIA)		290.95	288.77
TANK TEMPERATURES (°C)			
TANK 1		16.97	16.97
TANK 2		16.39	16.39
TANK 3		18.00	18.00
TANK 4[a]		14.26	14.26
HYDRAZINE REMAINING (POUNDS)			
TANK 1		55.30	55.07
TANK 2		55.30	55.07
TANK 3		55.30	55.07
TANK 4		342.57	341.98
TOTAL FUEL		508.47	507.19
TOTAL SPACECRAFT WEIGHT		4282.74	4281.46
THRUSTERS			
ORBIT ADJUST THRUSTERS USED		A1, B1, C1, D1	
TOTAL ORBIT ADJUST THRUSTER DURATION (sec)[b]		51.908	
TOTAL ATTITUDE THRUSTER DURATION (sec)		73.640	
SPACECRAFT ATTITUDE (deg)[c]			
PITCH		0.0	
YAW		0.0	
ROLL		0.0	
MANEUVER CALIBRATION			
SEMIMAJOR AXIS CHANGE (km)			
PREDICTED		1.1922	
OBSERVED		1.1908	
INCLINATION CHANGE (deg)			
PREDICTED		N/A	
OBSERVED		N/A	
THRUST CORRECTION FACTOR			
USED FOR PLANNING		1.0000	
RECALIBRATED[d]		0.9988	

9667(54a*)/84

[a]TANK 4 IS THE AUXILLIARY TANK KIT (ATK)

[b]BURN TIME INPUT TO GENERAL MANEUVER PROGRAM (GMAN) = TOTAL DURATION ÷ NUMBER OF THRUSTERS

[c]SPACECRAFT ATTITUDE AS INPUT TO GMAN FOR MANEUVER MODELING

[d]RECALIBRATED THRUST CORRECTION FACTOR = (OBSERVED ÷ PREDICTED) × FACTOR USED FOR PLANNING

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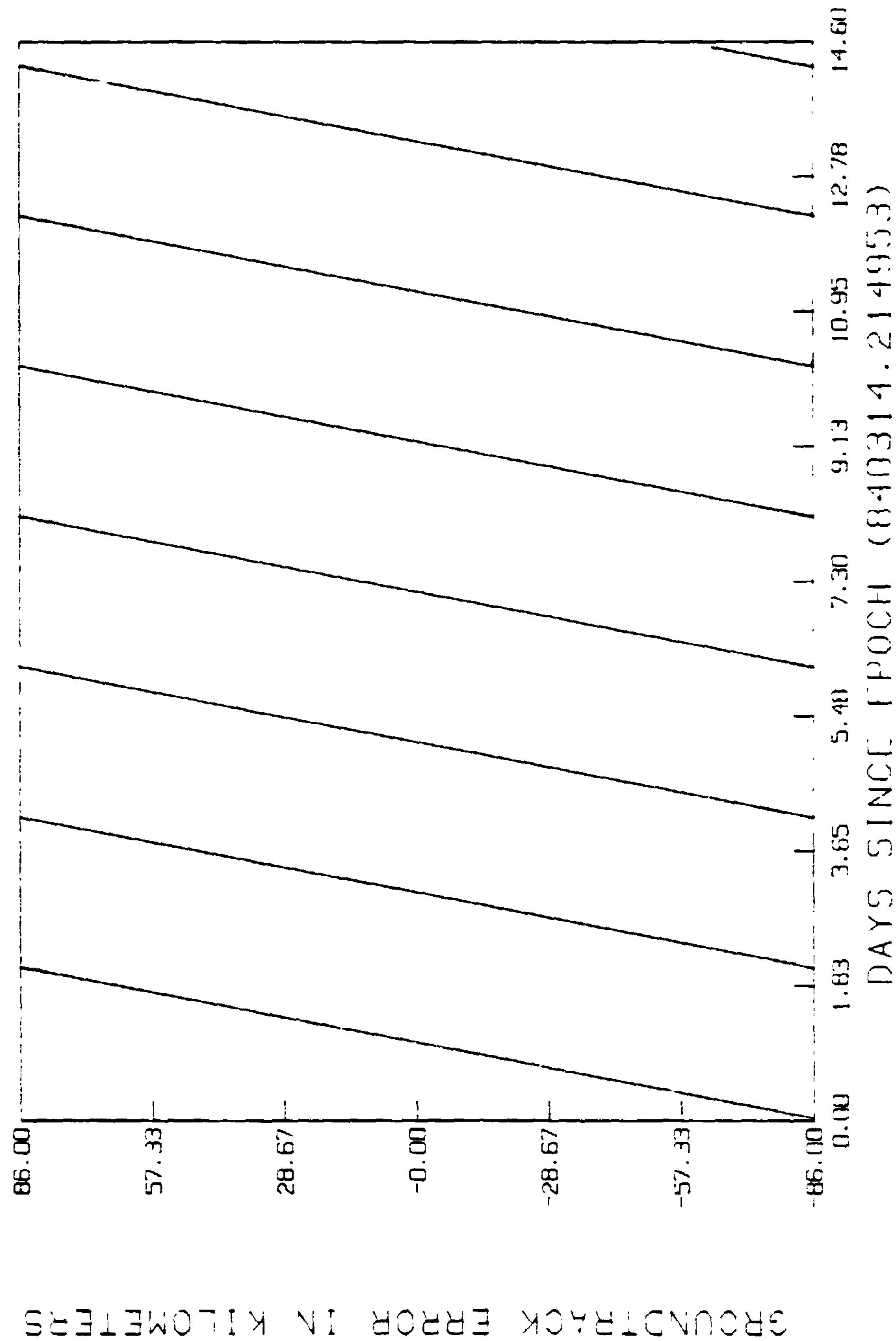

Figure A-7. Groundtrack Evolution Between Maneuvers 3 and 4

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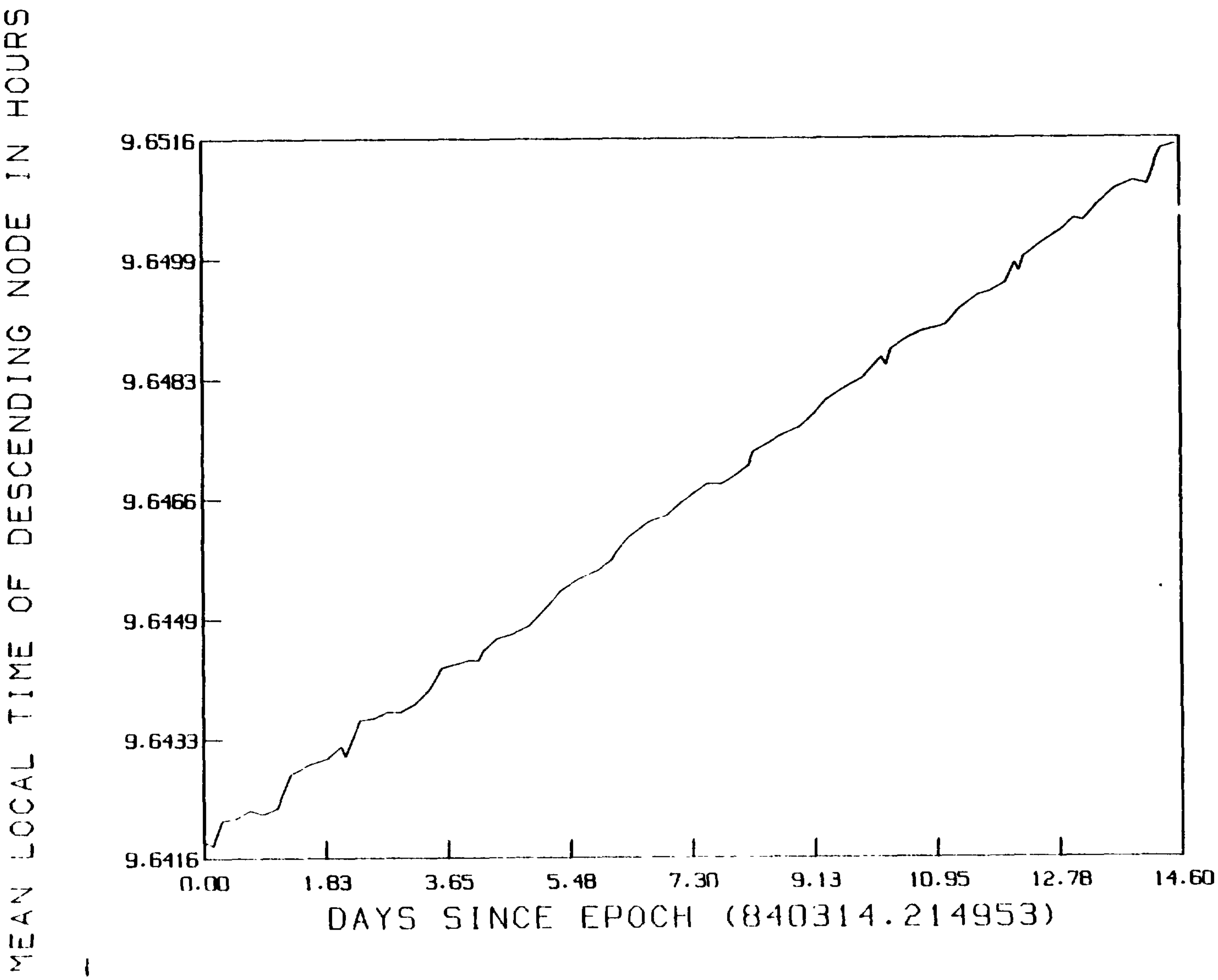

Figure A-8. Mean Local Time of Descending Node Between Maneuvers 3 and 4

Table A-9. Orbit Parameters for Maneuver 5

MANEUVER 5	ORBIT 405	DATE 840329	BURN START TIME (GMT) 124654	
OSCULATING ELEMENTS[a]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	
a	7071.3532	7073.4825	7073.6564	
e	0.0016267	0.0013346	0.0013046	
i	98.2501886	98.2504169	98.2508862	
Ω	151.87903	151.87885	151.87867	
ω	151.38186	154.36411	152.92971	
M	170.89719	167.91250	169.35032	
EPOCH (YYMMDD)	840329	840329	840329	
(HHMMSS)	124724.336	124724.336	124724.336	
AVERAGED ELEMENTS[b]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	CHANGE (OBSERVED – PREBURN)
$\bar{a}$	7069.0767	7071.2072	7071.3814	2.3047
$\bar{e}$	0.0012692	0.0009680	0.0009519	−0.0003173
$\bar{i}$	98.2511642	98.2513924	98.2518617	0.0006975
$\bar{\Omega}$	151.87381	151.87363	151.87345	−0.00036
$\bar{\omega}$	134.78209	133.74731	131.26110	−3.52099
$\bar{M}$	187.55100	188.58334	191.07296	3.52196
EPOCH (YYMMDD)	840329	840329	840329	
(HHMMSS)	124724.336	124724.336	124724.336	
PERIOD (sec)	5915.00	5917.68	5917.90	2.90
PERIGEE ALTITUDE[c]	681.9646	686.2223	686.5102	
APOGEE ALTITUDE[c]	699.9088	699.9121	699.9726	
$\bar{e}$ COS $\bar{\omega}$	−0.0008940	−0.0006694	−0.0006278	
$\bar{e}$ SIN $\bar{\omega}$	0.0009009	0.0006993	0.0007156	
GROUNDTRACK ERROR (km)[d]	−56.8			
MEAN LOCAL TIME OF DESCENDING NODE (HHMMSS)	093905			

[a] a = SEMIMAJOR AXIS (km)
e = ECCENTRICITY
i = INCLINATION (deg)
Ω = RIGHT ASCENSION OF ASCENDING NODE (deg)
ω = ARGUMENT OF PERIGEE (deg)
M = MEAN ANOMALY (deg)
TIMES ARE GMT

[b] NUMERICALLY AVERAGED OVER ONE ORBIT

[c] EQUATORIAL REFERENCE

[d] DISTANCE EAST (+) OR WEST (−) OF WORLD REFERENCE SYSTEM PATH

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Table A-10. Spacecraft Parameters for Maneuver 5

MANEUVER	ORBIT	DATE	BURN START TIME (GMT)
5	405	840329	124654

SPACECRAFT PARAMETERS	PREBURN	POSTBURN
FUEL SYSTEM PRESSURE (PSIA)	288.77	284.59
TANK TEMPERATURES (°C)		
TANK 1	16.97	16.97
TANK 2	16.39	16.39
TANK 3	18.00	18.00
TANK 4[a]	14.26	14.26
HYDRAZINE REMAINING (POUNDS)		
TANK 1	55.07	54.62
TANK 2	55.07	54.62
TANK 3	55.07	54.62
TANK 4	341.98	340.82
TOTAL FUEL	507.19	504.68
TOTAL SPACECRAFT WEIGHT	4281.46	4278.95

THRUSTERS	
ORBIT ADJUST THRUSTERS USED	A1, B1, C1
TOTAL ORBIT ADJUST THRUSTER DURATION (sec)[b]	91.008
TOTAL ATTITUDE THRUSTER DURATION (sec)	188.440
SPACECRAFT ATTITUDE (deg)[c]	
PITCH	0.0
YAW	0.0
ROLL	0.0
MANEUVER CALIBRATION	
SEMIMAJOR AXIS CHANGE (km)	
PREDICTED	2.1305
OBSERVED	2.3047
INCLINATION CHANGE (deg)	
PREDICTED	N/A
OBSERVED	N/A
THRUST CORRECTION FACTOR	
USED FOR PLANNING	1.0000
RECALIBRATED[d]	1.0821

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[a]TANK 4 IS THE AUXILLIARY TANK KIT (ATK)

[b]BURN TIME INPUT TO GENERAL MANEUVER PROGRAM (GMAN) = TOTAL DURATION ÷ NUMBER OF THRUSTERS

[c]SPACECRAFT ATTITUDE AS INPUT TO GMAN FOR MANEUVER MODELING

[d]RECALIBRATED THRUST CORRECTION FACTOR = (OBSERVED ÷ PREDICTED) × FACTOR USED FOR PLANNING

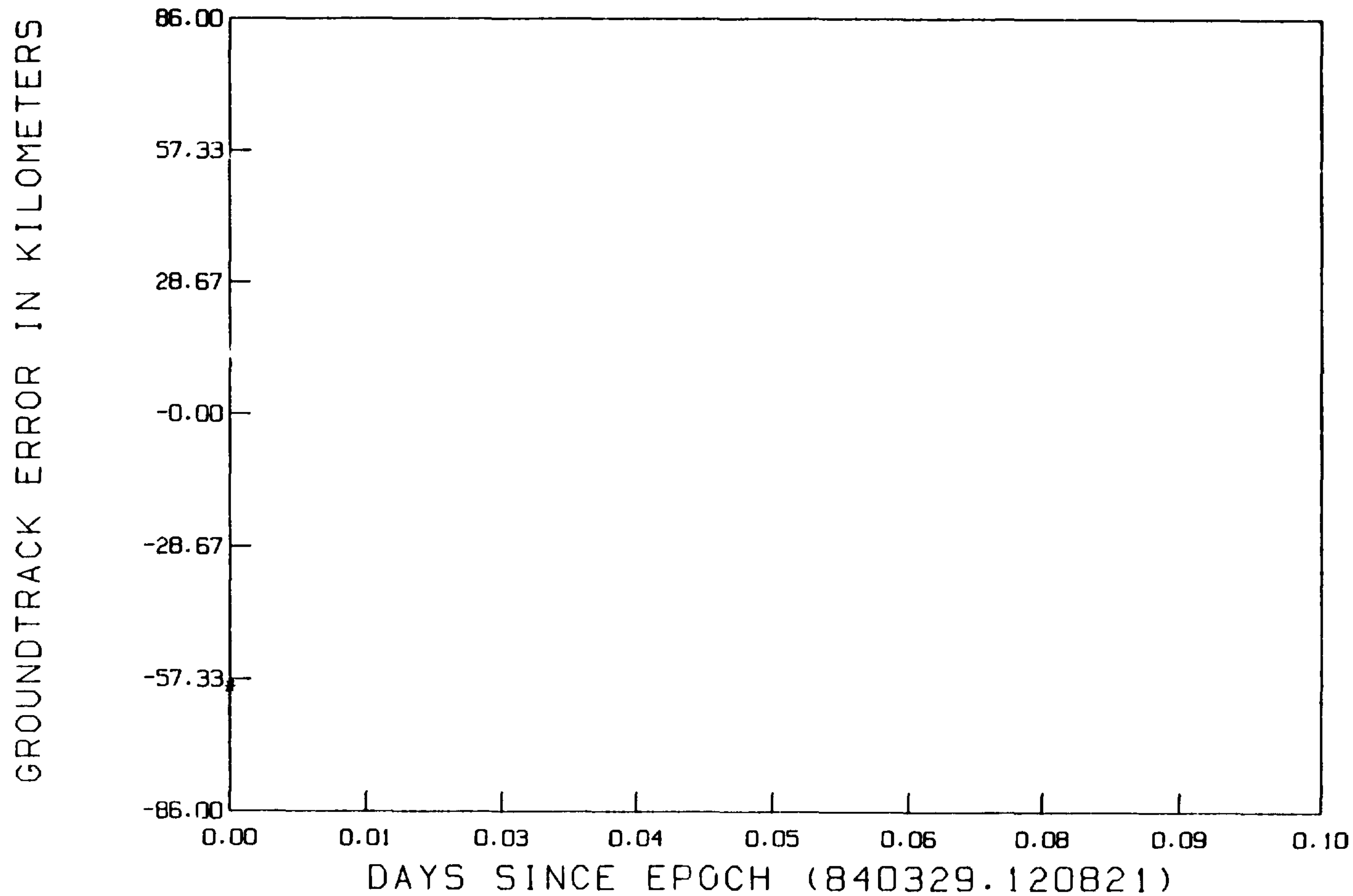

Figure A-9. Groundtrack Evolution Between Maneuvers 4 and 5

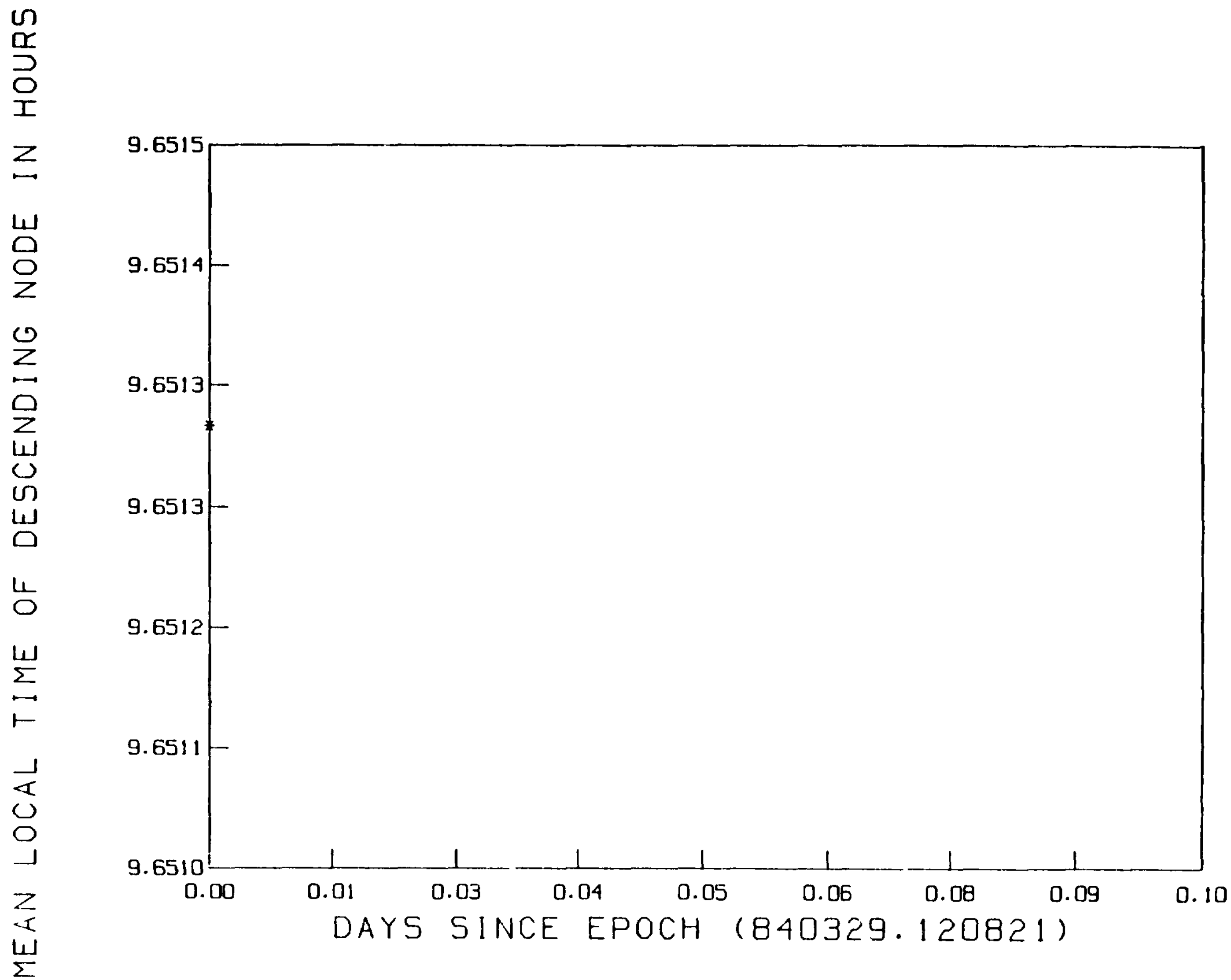

Figure A-10. Mean Local Time of Descending Node Between Maneuvers 4 and 5

Table A-11. Orbit Parameters for Maneuver 6

MANEUVER 6	ORBIT 425	DATE 840330	BURN START TIME (GMT) 214803	
OSCULATING ELEMENTS[a]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	
a	7079.3195	7081.2337	7081.1839	
e	0.0006356	0.0004229	0.0004362	
i	98.2476709	98.2479092	98.2475255	
Ω	153.24346	153.24339	153.24351	
ω	130.73293	112.10526	111.82824	
M	214.55183	233.17716	233.45481	
EPOCH (YYMMDD)	840330	840330	840330	
(HHMMSS)	214843.928	214843.928	214843.928	
AVERAGED ELEMENTS[b]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	CHANGE (OBSERVED – PREBURN)
$\bar{a}$	7071.3692	7073.2814	7073.2318	1.8626
$\bar{e}$	0.0010242	0.0007998	0.0008125	−0.0002117
$\bar{i}$	98.2523636	98.2526012	98.2522172	−0.0001464
$\bar{\Omega}$	153.24053	153.24046	153.24058	0.00005
$\bar{\omega}$	131.11557	121.50841	121.20780	−9.90777
$\bar{M}$	214.19665	223.80147	224.10271	9.90606
EPOCH (YYMMDD)	840330	840330	840330	
(HHMMSS)	214843.928	214843.928	214843.928	
PERIOD (sec)	5917.88	5920.28	5920.22	2.34
PERIGEE ALTITUDE[c]	685.9867	689.4842	689.3448	
APOGEE ALTITUDE[c]	700.4717	700.7986	700.8388	
$\bar{e}$ COS $\bar{\omega}$	−0.0006735	−0.0004180	−0.0004210	
$\bar{e}$ SIN $\bar{\omega}$	0.0007716	0.0006819	0.0006949	
GROUNDTRACK ERROR (km)[d]	18.4			
MEAN LOCAL TIME OF DESCENDING NODE (HHMMSS)	093908			

[a] a = SEMIMAJOR AXIS (km)
e = ECCENTRICITY
i = INCLINATION (deg)
Ω = RIGHT ASCENSION OF ASCENDING NODE (deg)
ω = ARGUMENT OF PERIGEE (deg)
M = MEAN ANOMALY (deg)
TIMES ARE GMT

[b] NUMERICALLY AVERAGED OVER ONE ORBIT

[c] EQUATORIAL REFERENCE

[d] DISTANCE EAST (+) OR WEST (−) OF WORLD REFERENCE SYSTEM PATH

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Table A-12. Spacecraft Parameters for Maneuver 6

MANEUVER	ORBIT	DATE	BURN START TIME (GMT)
6	425	840330	214803

SPACECRAFT PARAMETERS	PREBURN	POSTBURN
FUEL SYSTEM PRESSURE (PSIA)	284.24	281.06
TANK TEMPERATURES (°C)		
TANK 1	17.11	17.11
TANK 2	16.40	16.40
TANK 3	18.06	18.06
TANK 4[a]	13.95	13.95
HYDRAZINE REMAINING (POUNDS)		
TANK 1	54.62	54.26
TANK 2	54.62	54.26
TANK 3	54.62	54.26
TANK 4	340.82	339.92
TOTAL FUEL	504.68	502.70
TOTAL SPACECRAFT WEIGHT	4278.95	4276.97

THRUSTERS	
ORBIT ADJUST THRUSTERS USED	A1, C1
TOTAL ORBIT ADJUST THRUSTER DURATION (sec)[b]	81.856
TOTAL ATTITUDE THRUSTER DURATION (sec)	87.360
SPACECRAFT ATTITUDE (deg)[c]	
PITCH	0.0
YAW	0.0
ROLL	0.0
MANEUVER CALIBRATION	
SEMIMAJOR AXIS CHANGE (km)	
PREDICTED	1.9123
OBSERVED	1.8626
INCLINATION CHANGE (deg)	
PREDICTED	N/A
OBSERVED	N/A
THRUST CORRECTION FACTOR	
USED FOR PLANNING	1.0000
RECALIBRATED[d]	0.9739

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[a]TANK 4 IS THE AUXILLIARY TANK KIT (ATK)

[b]BURN TIME INPUT TO GENERAL MANEUVER PROGRAM (GMAN) = TOTAL DURATION ÷ NUMBER OF THRUSTERS

[c]SPACECRAFT ATTITUDE AS INPUT TO GMAN FOR MANEUVER MODELING

[d]RECALIBRATED THRUST CORRECTION FACTOR = (OBSERVED ÷ PREDICTED) × FACTOR USED FOR PLANNING

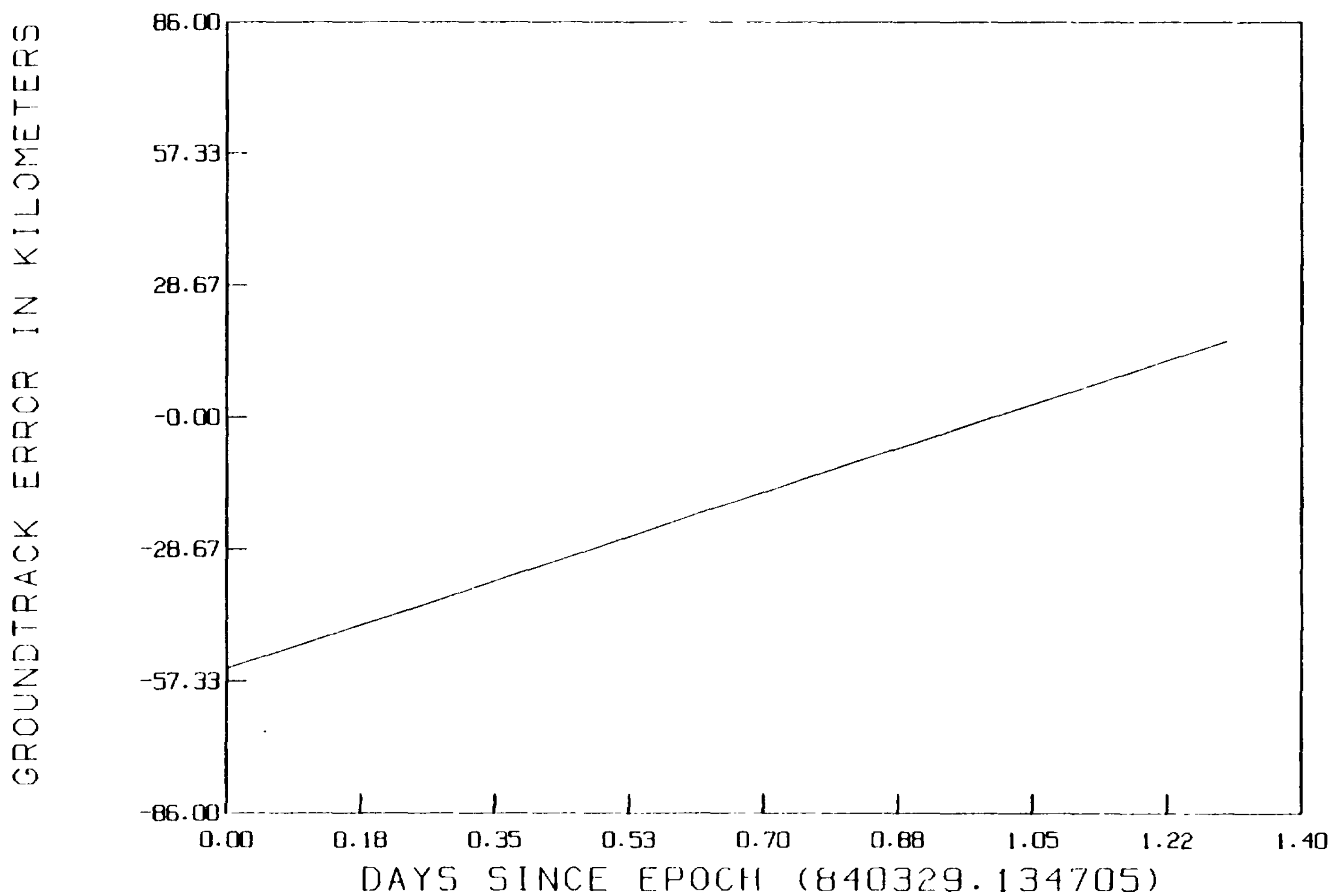

Figure A-11. Groundtrack Evolution Between Maneuvers 5 and 6

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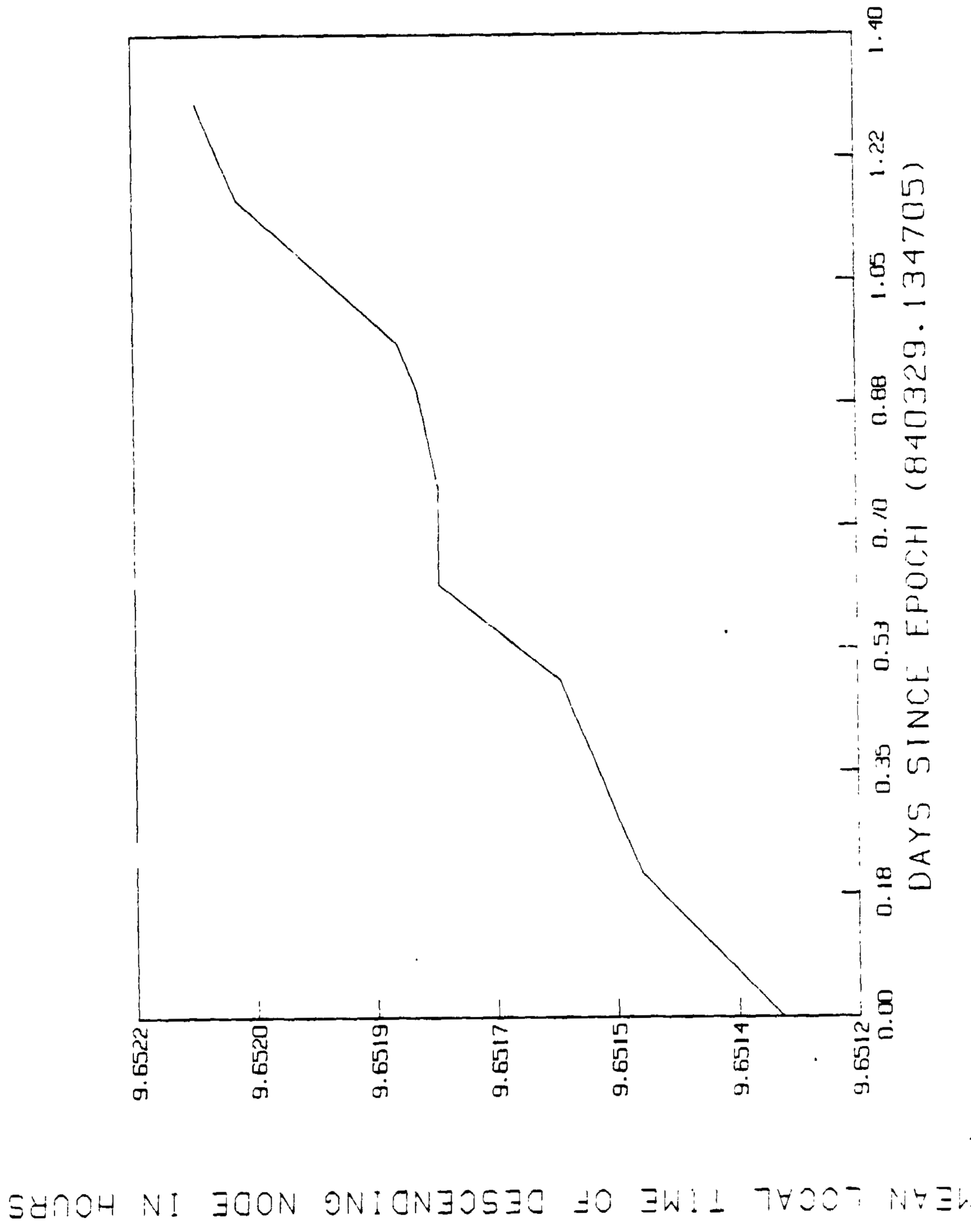

Figure A-12. Mean Local Time of Descending Node Between Maneuvers 5 and 6

Table A-13. Orbit Parameters for Maneuver 7

MANEUVER 7	ORBIT 469	DATE 840402	BURN START TIME (GMT) 205004	
OSCULATING ELEMENTS[a]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	
a	7075.6386	7078.3570	7078.2720	
e	0.0013429	0.0012923	0.0012989	
i	98.2492276	98.2495193	98.2499165	
Ω	156.17316	156.17337	156.17369	
ω	138.31083	121.66387	122.18392	
M	259.32621	275.96968	275.45000	
EPOCH (YYMMDD)	840402	840402	840402	
(HHMMSS)	205102.432	205102.432	205102.432	
AVERAGED ELEMENTS[b]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	CHANGE (OBSERVED – PREBURN)
$\bar{a}$	7073.2325	7075.9524	7075.8673	2.6348
$\bar{e}$	0.0009096	0.0009865	0.0009882	0.0000786
$\bar{i}$	98.2505715	98.2508630	98.2512603	0.0006888
$\bar{\Omega}$	156.17840	156.17861	156.17894	0.00054
$\bar{\omega}$	122.67551	99.73043	100.50609	−22.16942
$\bar{M}$	274.90897	297.85057	297.07528	22.16631
EPOCH (YYMMDD)	840402	840402	840402	
(HHMMSS)	205102.432	205102.432	205102.432	
PERIOD (sec)	5920.22	5923.63	5923.53	3.31
PERIGEE ALTITUDE[c]	688.6587	690.8320	690.7349	
APOGEE ALTITUDE[c]	701.5263	704.7928	704.7197	
$\bar{e}$ COS $\bar{\omega}$	−0.0004911	−0.0001667	−0.0001802	
$\bar{e}$ SIN $\bar{\omega}$	0.0007656	0.0009723	0.0009716	
GROUNDTRACK ERROR (km)[d]	−38.0			
MEAN LOCAL TIME OF DESCENDING NODE (HHMMSS)	093913			

[a] a = SEMIMAJOR AXIS (km)
e = ECCENTRICITY
i = INCLINATION (deg)
Ω = RIGHT ASCENSION OF ASCENDING NODE (deg)
ω = ARGUMENT OF PERIGEE (deg)
M = MEAN ANOMALY (deg)
TIMES ARE GMT

[b] NUMERICALLY AVERAGED OVER ONE ORBIT

[c] EQUATORIAL REFERENCE

[d] DISTANCE EAST (+) OR WEST (−) OF WORLD REFERENCE SYSTEM PATH

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Table A-14. Spacecraft Parameters for Maneuver 7

MANEUVER	ORBIT	DATE	BURN START TIME (GMT)
7	469	840402	205004

SPACECRAFT PARAMETERS	PREBURN	POSTBURN
FUEL SYSTEM PRESSURE (PSIA)	280.89	276.54
TANK TEMPERATURES (°C)		
TANK 1	16.94	16.94
TANK 2	16.39	16.39
TANK 3	17.87	17.87
TANK 4[a]	13.94	13.94
HYDRAZINE REMAINING (POUNDS)		
TANK 1	54.26	53.77
TANK 2	54.26	53.77
TANK 3	54.26	53.77
TANK 4	339.92	338.64
TOTAL FUEL	502.70	499.95
TOTAL SPACECRAFT WEIGHT	4276.97	4274.22

THRUSTERS	
ORBIT ADJUST THRUSTERS USED	A1, C1
TOTAL ORBIT ADJUST THRUSTER DURATION (sec)[b]	116.864
TOTAL ATTITUDE THRUSTER DURATION (sec)	111.160
SPACECRAFT ATTITUDE (deg)[c]	
PITCH	0.0
YAW	0.0
ROLL	0.0
MANEUVER CALIBRATION	
SEMIMAJOR AXIS CHANGE (km)	
PREDICTED	2.7199
OBSERVED	2.6348
INCLINATION CHANGE (deg)	
PREDICTED	N/A
OBSERVED	N/A
THRUST CORRECTION FACTOR	
USED FOR PLANNING	1.0000
RECALIBRATED[d]	0.9686

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[a]TANK 4 IS THE AUXILLIARY TANK KIT (ATK)

[b]BURN TIME INPUT TO GENERAL MANEUVER PROGRAM (GMAN) = TOTAL DURATION ÷ NUMBER OF THRUSTERS

[c]SPACECRAFT ATTITUDE AS INPUT TO GMAN FOR MANEUVER MODELING

[d]RECALIBRATED THRUST CORRECTION FACTOR = (OBSERVED ÷ PREDICTED) × FACTOR USED FOR PLANNING

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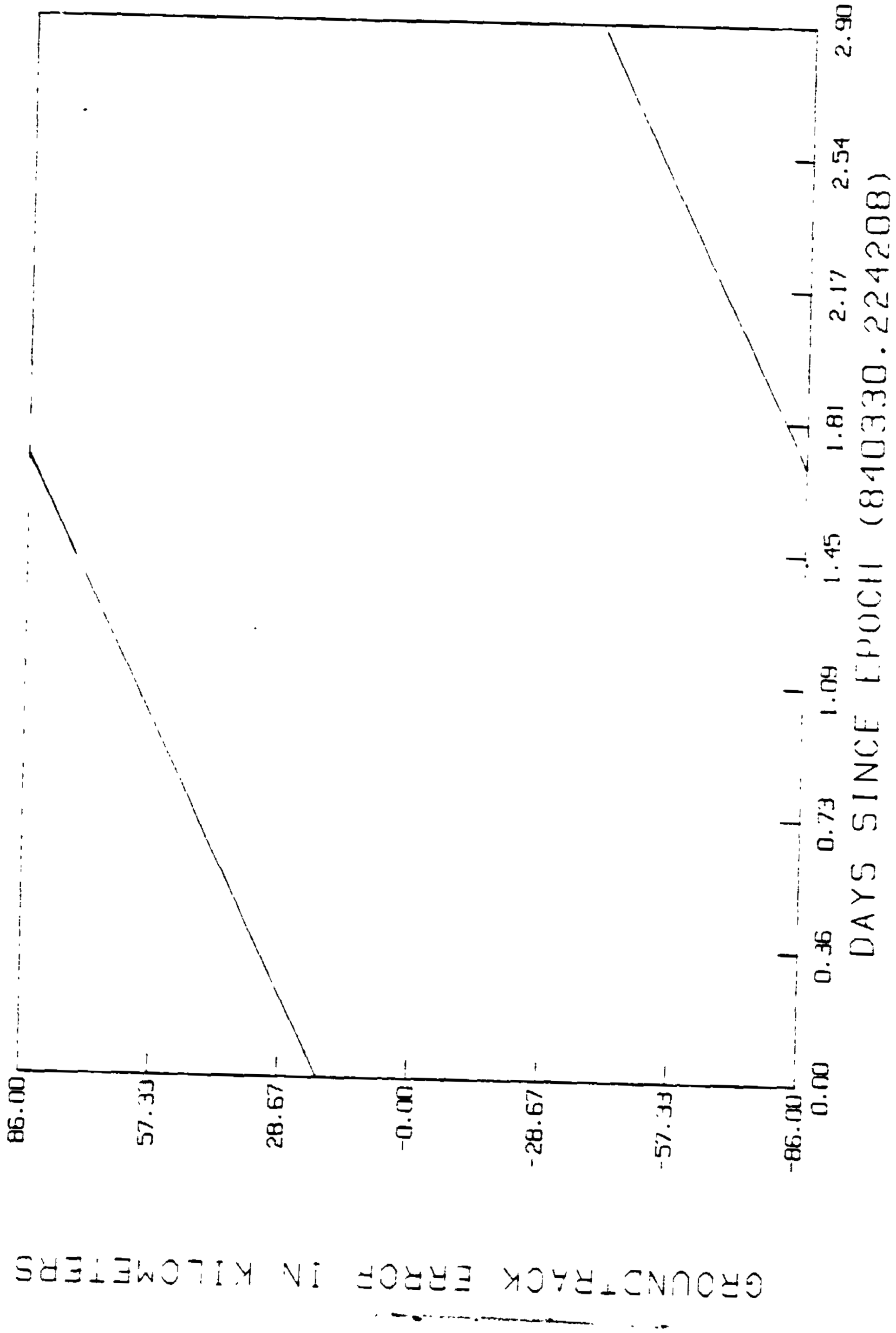

Figure A-13. Groundtrack Evolution Between Maneuvers 6 and 7

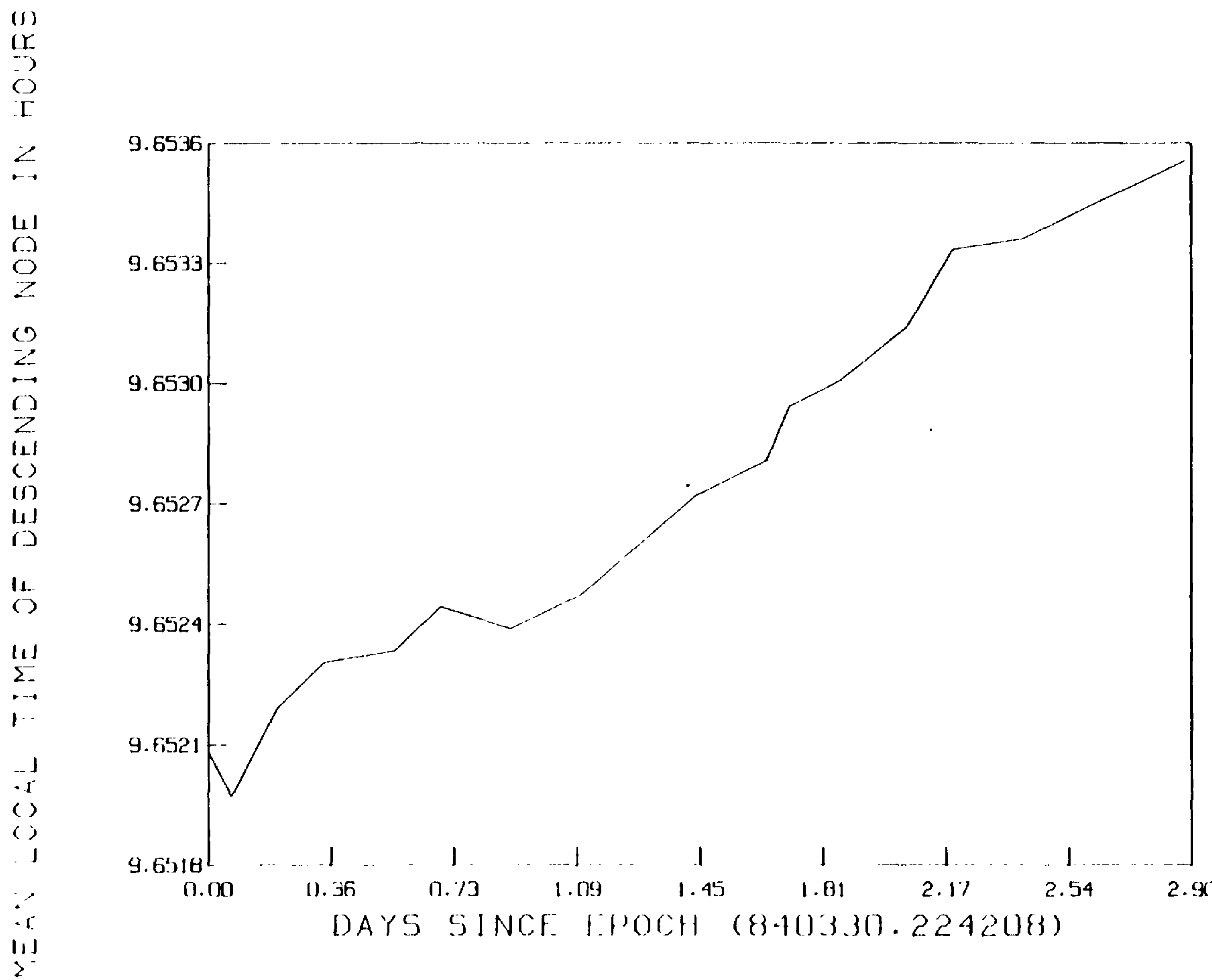

Figure A-14. Mean Local Time of Descending Node Between Maneuvers 6 and 7

Table A-15. Orbit Parameters for Maneuver 8

MANEUVER 8	ORBIT 498	DATE 840404	BURN START TIME (GMT) 203807	
OSCULATING ELEMENTS[a]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	
a	7076.7887	7078.7104	7078.6954	
e	0.0012938	0.0013032	0.0013079	
i	98.2498010	98.2499952	98.2500920	
Ω	158.14790	158.14807	158.14817	
ω	131.72728	119.71375	119.83421	
M	270.63163	282.64287	282.52265	
EPOCH (YYMMDD)	840404	840404	840404	
(HHMMSS)	203850.168	203850.168	203850.168	
AVERAGED ELEMENTS[b]	PREBURN	PREDICTED POSTBURN	OBSERVED POSTBURN	CHANGE (OBSERVED – PREBURN)
$\bar{a}$	7075.8637	7077.7872	7077.7722	1.9085
$\bar{e}$	0.0010086	0.0011542	0.0011569	0.0001483
$\bar{i}$	98.2502575	98.2504517	98.2505485	0.0002910
$\bar{\Omega}$	158.15332	158.15349	158.15359	0.00027
$\bar{\omega}$	101 61489	89.40040	89.63688	−11.97801
$\bar{M}$	300 68983	312.90205	312.66582	11.97599
EPOCH (YYMMDD)	840404	840404	840404	
(HHMMSS)	203850.168	203850.168	203850.168	
PERIOD (sec)	5923.52	5925.94	5925.92	2.40
PERIGEE ALTITUDE[c]	690.5870	691.4780	691.4439	
APOGEE ALTITUDE[c]	704.8604	707.8104	707.8205	
$\bar{e}$ COS $\bar{\omega}$	−0.0002031	0.0000121	0.0000073	
$\bar{e}$ SIN $\bar{\omega}$	0.0009879	0.0011541	0.0011569	
GROUNDTRACK ERROR (km)[d]	−4.9			
MEAN LOCAL TIME OF DESCENDING NODE (HHMMSS)	093915			

[a] a = SEMIMAJOR AXIS (km)
e = ECCENTRICITY
i = INCLINATION (deg)
Ω = RIGHT ASCENSION OF ASCENDING NODE (deg)
ω = ARGUMENT OF PERIGEE (deg)
M = MEAN ANOMALY (deg)
TIMES ARE GMT

[b] NUMERICALLY AVERAGED OVER ONE ORBIT

[c] EQUATORIAL REFERENCE

[d] DISTANCE EAST (+) OR WEST (−) OF WORLD REFERENCE SYSTEM PATH

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Table A-16. Spacecraft Parameters for Maneuver 8

MANEUVER	ORBIT	DATE	BURN START TIME (GMT)
8	498	840404	203807

SPACECRAFT PARAMETERS	PREBURN	POSTBURN
FUEL SYSTEM PRESSURE (PSIA)	275.21	272.16
TANK TEMPERATURES (°C)		
TANK 1	16.78	16.78
TANK 2	16.39	16.39
TANK 3	17.82	17.82
TANK 4[a]	13.77	13.77
HYDRAZINE REMAINING (POUNDS)		
TANK 1	53.77	53.40
TANK 2	53.77	53.40
TANK 3	53.77	53.40
TANK 4	338.64	337.72
TOTAL FUEL	499.95	497.92
TOTAL SPACECRAFT WEIGHT	4274.22	4272.19

THRUSTERS	
ORBIT ADJUST THRUSTERS USED	A1, C1
TOTAL ORBIT ADJUST THRUSTER DURATION (sec)[b]	86.336
TOTAL ATTITUDE THRUSTER DURATION (sec)	83.440
SPACECRAFT ATTITUDE (deg)[c]	
PITCH	0.0
YAW	0.0
ROLL	0.0
MANEUVER CALIBRATION	
SEMIMAJOR AXIS CHANGE (km)	
PREDICTED	1.9235
OBSERVED	1.9085
INCLINATION CHANGE (deg)	
PREDICTED	N/A
OBSERVED	N/A
THRUST CORRECTION FACTOR	
USED FOR PLANNING	0.9700
RECALIBRATED[d]	0.9624

9667(54c*)/84

[a]TANK 4 IS THE AUXILLIARY TANK KIT (ATK)

[b]BURN TIME INPUT TO GENERAL MANEUVER PROGRAM (GMAN) = TOTAL DURATION ÷ NUMBER OF THRUSTERS

[c]SPACECRAFT ATTITUDE AS INPUT TO GMAN FOR MANEUVER MODELING

[d]RECALIBRATED THRUST CORRECTION FACTOR = (OBSERVED ÷ PREDICTED) × FACTOR USED FOR PLANNING

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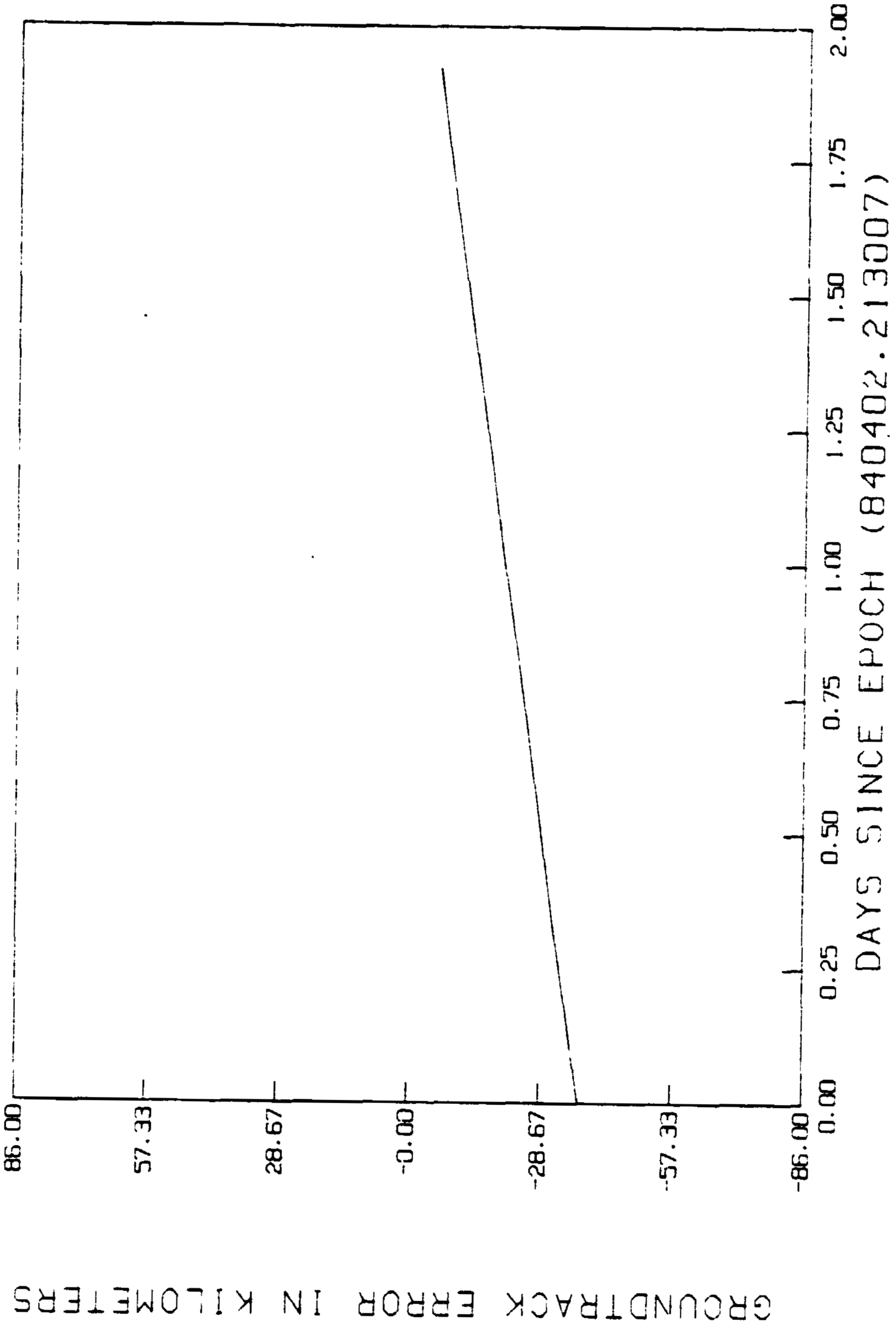

Figure A-15. Groundtrack Evolution Between Maneuvers 7 and 8

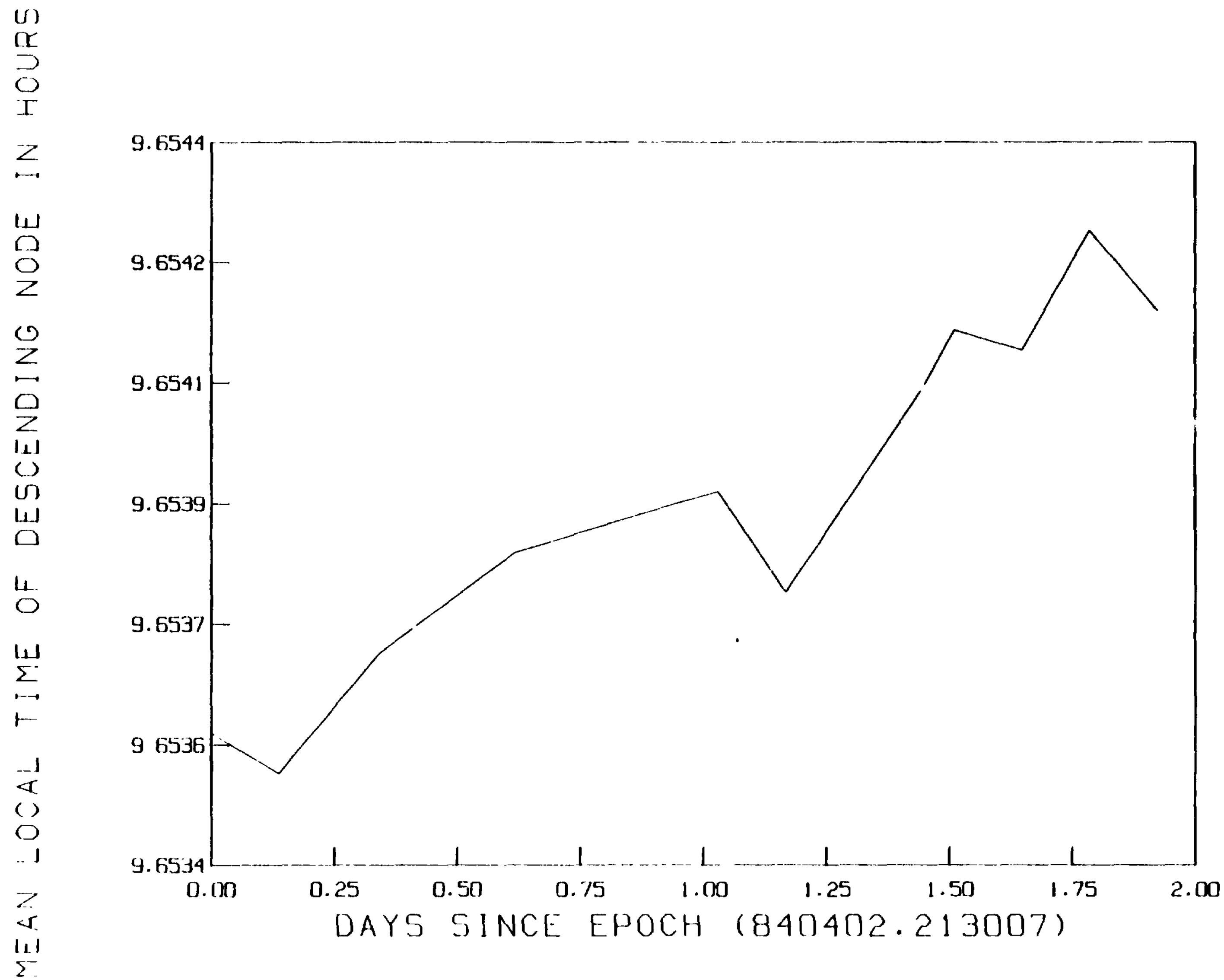

Figure A-16. Mean Local Time of Descending Node Between Maneuvers 7 and 8

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